S.F. Personius PALEOSEISMOLOGY OF UTAH, VOLUME 2 UGMS Special Studies 76

Paleoseismology of Utah, Volume 2

PALEOSEISMIC ANALYSIS OF THE WASATCH FAULT ZONE AT THE BRIGHAM CITY TRENCH SITE, BRIGHAM CITY, UTAH AND POLE PATCH TRENCH SITE, PLEASANT VIEW, UTAH

by
Stephen F. Personius
U.S. Geological Survey, Denver, Colorado

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UTAH GEOLOGICAL AND MINERAL SURVEY
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PREFACE

This UGMS Special Studies, the second in the "Paleoseismology of Utah" Special Studies series, consists of two reports by Stephen F. Personius of the U.S. Geological Survey (USGS) on fault-trenching studies of the north-central part of the Wasatch fault zone. The studies were undertaken as part of the joint USGS/UGMS Wasatch Front Earthquake Hazard and Risk Assessment Program, a 5-year research effort conducted under the auspices of the National Earthquake Hazard Reduction Program to evaluate earthquake hazard and risk along Utah's heavily populated Wasatch Front.

Trenching studies such as those reported here provide information on earthquake timing and recurrence, fault displacement, and fault geometry that is used to characterize seismic-source zones and to evaluate the long-term earthquake potential of active faults. The UGMS is doubly pleased to publish this special study, first, because it makes important paleoseismic information available to those charged with mitigating earthquake risk on the Wasatch Front, and second, because it is tangible evidence of the close cooperation that exists at the State and Federal levels on an issue that affects the life, safety, and well being of the citizens of Utah.

William R. Lund, Series Editor
Utah Geological and Mineral Survey

Paleoseismology of Utah, Volume 2

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by
Stephen F. Personius
U.S. Geological Survey, Denver, Colorado

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PALEOSEISMIC ANALYSIS OF THE WASATCH FAULT ZONE AT THE BRIGHAM CITY TRENCH SITE, BRIGHAM CITY, UTAH

by
Stephen F. Personius
U.S. Geological Survey, Denver, Colorado

ABSTRACT

In September 1986, trench BC-1 was excavated across an 8-m-high (26 ft) fault scarp on the Brigham City segment of the Wasatch fault zone near Brigham City, Utah. The trench exposed a complex, 4-m-wide (13 ft) zone of "stepped" normal faults that offset a sequence of lower and middle Holocene alluvial-fan deposits about 6 m (20 ft). A series of fault-scarp colluvial wedges and several apparent mean-residence-time (AMRT) ^{14}C ages on buried soils provide evidence for three normal-slip surface-faulting events. The first (oldest) event consisted of about 2.5 m (8.2 ft) of vertical displacement; although undated, this event probably occurred 5 to 7 ka. The second event consisted of about 2.5 m (8.2 ft) of vertical displacement; AMRT ^{14}C ages suggest that this event occurred about 4.7 ± 0.5 ka. The third (youngest) event consisted of about 1.0 m (3.3 ft) of vertical displacement; AMRT ^{14}C ages suggest that this event occurred about 3.6 ± 0.5 ka. These data yield an average displacement of 2 m (6.5 ft) per event, a single recurrence interval between the second and third events of 1100 ± 1000 years, and an elapsed time since the third event of 3600 ± 500 years. The timing of the second and third events yields a post-middle-Holocene slip rate of 0.75 ± 0.3 mm/yr (.03 ± .01 in/yr). Empirical analysis of historic earthquakes on normal faults suggests that the surface displacements of 1.0 to 2.5 m (3.3 - 8.2 ft) on the Brigham City segment were associated with earthquakes of magnitude (M_S) 6.8 to 7.1.

The long elapsed time since the third event and the apparent decrease in displacement associated with this event suggest that the Brigham City segment may have experienced a decline in strain accumulation in late Holocene time. Alternatively, the segment may have entered a quiescent phase of strain accumulation between earthquake "clusters," or the segment may be continuing to accumulate strain at its middle-Holocene rate and is therefore overdue for another surface-faulting earthquake. Longer term recurrence data will be required to choose which of these scenarios best explains the pattern of recurrence of Holocene surface-faulting earthquakes on the Brigham City segment.

INTRODUCTION

The Brigham City trench (trench BC-1) was excavated and logged in September and October 1986 across a fault scarp on the Bowden Canyon alluvial fan on the eastern outskirts of Brigham City, Utah (figure 1), during field investigations and mapping of the Brigham City segment of the Wasatch fault zone (Personius, 1986, 1988a, b, 1990; Personius and Gill, (1987). Trenching studies in the Brigham City area were part of a larger effort to better define the timing of individual surface-faulting earthquakes along the more populated parts of the Wasatch fault zone (Machette and others, 1987, in press; Machette and Scott, 1988).

This report begins with a description of the Quaternary geologic setting of the region and some of the stratigraphic and structural relations in the Brigham City trench. The report continues with a description of the most likely sequence of faulting events and a discussion of the dating and timing of these events and concludes with a discussion of some seismologic implications of the Brigham City trench data. Throughout the report, the term "surface-faulting event" refers to an episode of surface faulting that presumably accompanied a large-magnitude earthquake on this part of the Wasatch fault zone. The terms "net vertical displacement" and "surface offset" refer to the vertical separation of a stratigraphic horizon or geomorphic surface across a fault zone. Fault-scarp terminology follows that of Bucknam and Anderson (1979). Locations of specific features referred to in the following discussion are given as a coordinate pair (x, y) from the corresponding axes on the trench log (page 10). Detailed descriptions of the units shown on the log are included in the appendix.

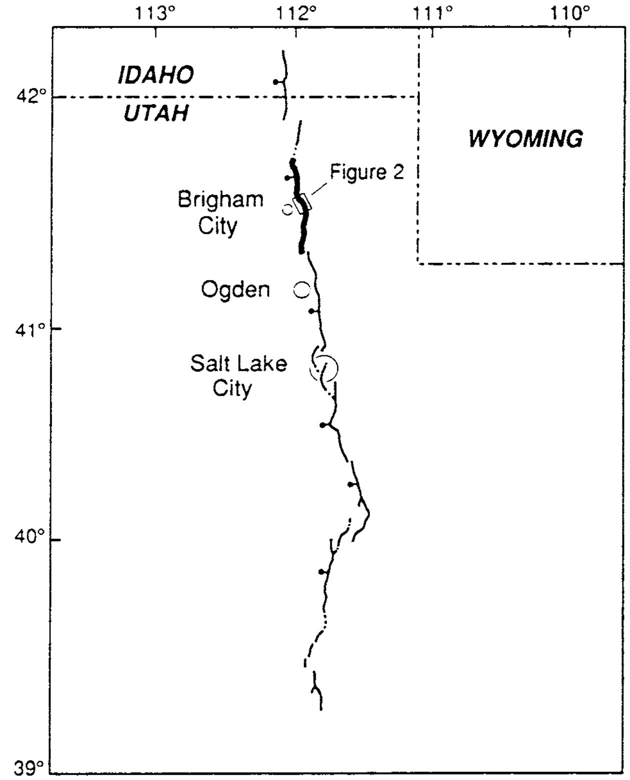


Figure 1. Index map showing trace of the Wasatch fault zone in southern Idaho and north-central Utah; heavier line marks the Brigham City segment. The location of figure 2 and the area of the Brigham City trench site is outlined with a box. Fault trace from Machette and others (1987, in press).

GEOLOGIC SETTING

The 40-km-long (25 mi) Brigham City segment (figure 1; Personius, 1988a, b, 1990) marks the northernmost extent of recurrent Holocene surface faulting on the Wasatch fault zone. Because Brigham City is located near the middle of the mapped trace of the segment, paleoseismic information derived from this investigation may be useful for characterizing Holocene movement on much of the segment.

The surficial geology along the northern Wasatch Front is dominated by lacustrine deposits of the latest cycle of Lake Bonneville, known as the Bonneville lake cycle (Scott and others, 1983; Currey and Oviatt, 1985). This cycle began 25 to 30 ka, when the lake began to rise from a level near the altitude of modern Great Salt Lake (1283 m or 4210 ft above mean sea level). The lake level rose to the altitude of the Bonneville shoreline (1584 m or 5200 ft) about 16 ka. About 15 ka, the lake overtopped its threshold near Red Rock Pass in southeastern Idaho. The resulting Bonneville flood rapidly lowered the level of the lake 115 m (380 ft) to the altitude of the Prove shoreline (1475 m or 4840 ft). The lake level stayed at the altitude of the Provo shoreline for a few thousand years before declining rapidly to the level of modern Great Salt Lake about 11 ka.

Alluvial fans were deposited concurrent with and following the retreat of Lake Bonneville from the Provo shoreline. The initial alluvial-fan deposits were fluvial gravels consisting of recycled lacustrine clasts, but warmer and drier conditions during middle Holocene time drastically reduced stream flows, and most of the sediment in the upper parts of these alluvial fans was deposited as debris flows. Although debris flows are still being deposited along the Wasatch Front (Wieczorek and others, 1983, 1989), most of the sediment in the fans in the Brigham City area was deposited in early to middle Holocene time (Personius, 1988a, 1990).

The Brigham City trench was located in lower to middle Holocene alluvial-fan deposits at the mouth of Bowden Canyon (figures 2, 3) at an altitude of 1365 m (4480 ft). Fault scarps in deposits of the Bonneville lake cycle adjacent to this fan are about 20 m (66 ft) high and have 12 to 15 m (39 - 49 ft) of surface offset, whereas at the trench site the fault scarp is only about 8 m (26 ft) high and has 5.5 m (18 ft) of surface offset (figure 4). The scarp is slightly smaller (4 m or 13 ft of surface offset) in a younger part of the Bowden Canyon fan northwest of the trench site. These changes in amount of surface offset along strike are clear geomorphic evidence of recurrent latest Pleistocene and Holocene movement on the Brigham City segment.

A possible complication at the Bowden Canyon site is the presence of a fault splay in Bonneville lake cycle deposits about 50 m (164 ft) northeast of the trench site (figures 2, 3); because this splay does not cut post-Bonneville lake-cycle deposits, I believe that all of the post-middle Holocene slip on this part of the Brigham City segment is recorded in the fault scarp trenched in this study.

TRENCH ANALYSIS

STRATIGRAPHY

The Brigham City trench site was covered by the waters of Lake Bonneville from 25 to 30 ka to about 12 ka (see lake hydrographs in Scott and others, 1983, and Curry and Oviatt, 1985). The stratigraphically lowest and oldest deposits in the trench (unit 10) are exposed east of fault F1 near the base of the trench. Unit 10 is a series of well-imbricated, moderately well-sorted sandy pebble and cobble gravels that consist almost entirely of subround to round, reworked lacustrine clasts. These gravels were probably deposited by streams shortly after the level of Lake Bonneville retreated below the altitude of the trench. The rest of the alluvial-fan sequence exposed in the trench consists of silty, poorly sorted debris-flow deposits (units 6, 7, 8-2, 9-2), and associated openwork levee or sieve (?) cobble and boulder gravels (units 8-1 and 9-1).

The ground surface that immediately predates the first surface-faulting event (hereafter referred to as the "pre-fault surface") is not well preserved in the hanging wall because this part of the trench has been drastically modified by post-first-event fluvial erosion. My best explanation for the complex stratigraphic relations in the lower part of the hanging wall is that unit 6 represents the eroded remnants of the pre-fault surface and unit 5-2 is a fluvial gravel deposited in a channel cut into this surface. Unit 5-1 is fault-scarp colluvium that later filled the eroded channel; this deposit may be a mixture of colluvium and alluvium.

The age of the pre-fault surface is problematic. In many trench excavations of normal faults, the pre-fault surface is marked by a buried soil that commonly contains enough carbon for radiocarbon dating. In the case of the Brigham City trench, any soil that may have existed on unit 6 prior to the first faulting event has been removed by erosion, and no other organic material was found that could be used to date this deposit. The only organic material recovered from the pre-fault deposits in the hanging wall was collected from a buried A horizon in unit 8-1 A. Unfortunately, an AMRT (apparent mean-residence-time; see discussion on radiocarbon age calibration below) ^{14}C age of 3610 ± 110 yr B.P. (radiocarbon years before 1950) obtained on this organic-rich sediment is significantly younger than AMRT ages on similar materials found stratigraphically higher in the trench. This inversion of ^{14}C ages suggests a mixing of organic matter from units 3-A

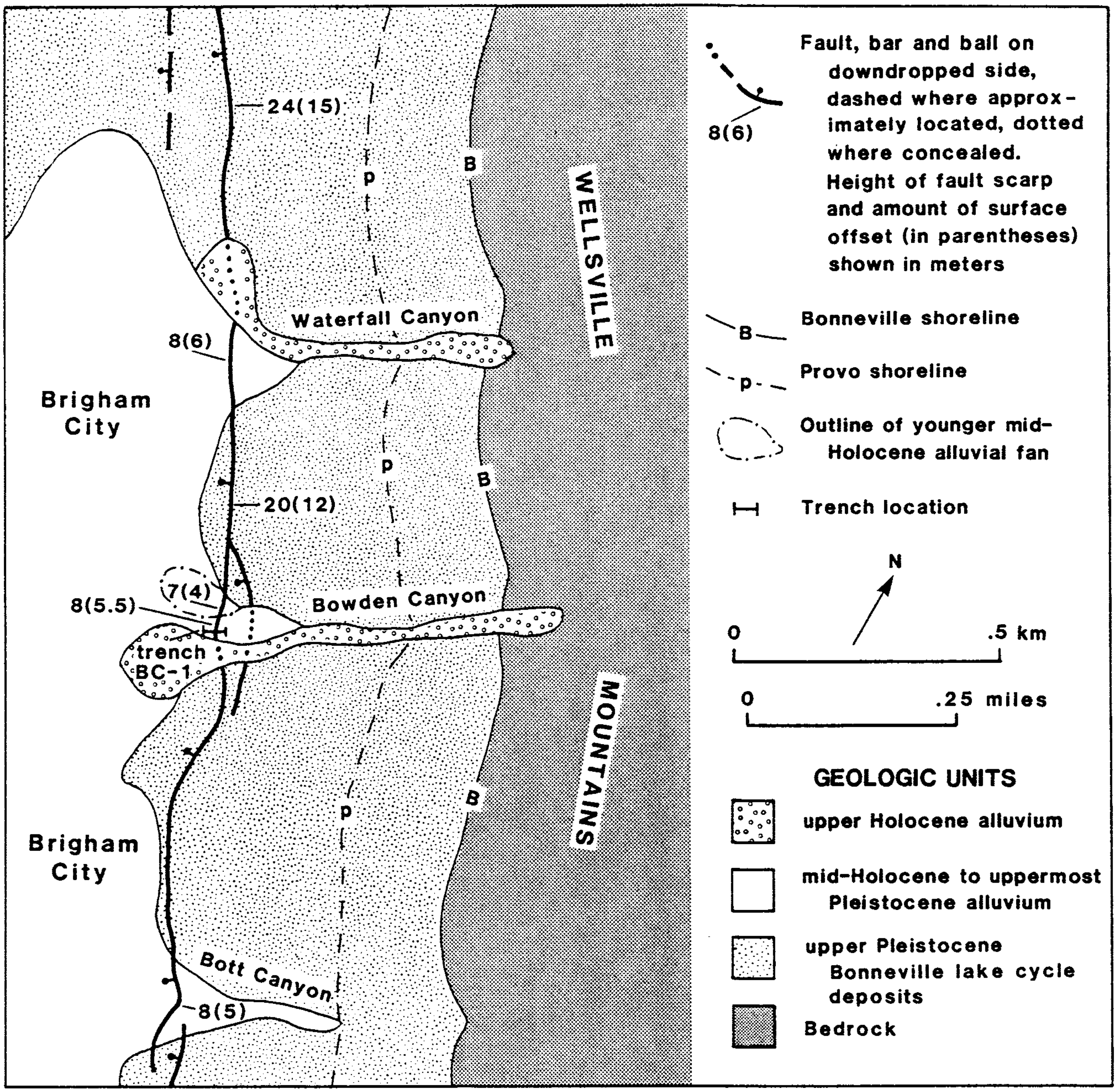


Figure 2. Geologic map of the Brigham City trench site; simplified from Personius (1988a, 1990). Location of map area shown in figure 1.

(AMRT ^{14}C age of 3430 ± 70 yr B.P.) and 5-1A (AMRT ^{14}C age of 4330 ± 70 yr B.P.), probably as a result of bioturbation by rodents, who commonly exploit openwork deposits for burrows. Unfortunately, no other suitable material for radiocarbon dating was obtained from the pre-fault deposits and therefore their age can only be estimated from other geologic considerations.

Several wedges of fault-scarp colluvium were exposed in the Brigham City trench. The relations between these scarp-colluvial deposits and the size and timing of individual faulting events will be described in later discussions of the sequence and timing of surface-faulting events.

STRUCTURES

The Brigham City trench exposed a complex, 4-m-wide (13 ft) zone of "stepped" normal faults, which I have grouped into three fault strands (F1, F2, and F3) for discussion purposes. Correlation of stratigraphic units is problematic, but I have tentatively correlated unit 8-1A across the fault zone because of similar stratigraphic position and because the apparent vertical stratigraphic displacement of this deposit (6 m or 20 ft) is about the same as the amount of surface offset (5.5 m or 18 ft) measured from a topographic profile across the fault scarp. Reconstruction of unit 8-1A and measurement of 6 m (20 ft) of displacement across the fault zone required removal of about 4° of backtilt of unit 8-1A in the hanging wall.

If the correlation of unit 8-1A across the fault zone is correct, then a total of about 6 m (20 ft) of net vertical displacement is recorded in the Brigham City trench. Net vertical displacement on faults F2 and F3 (1.6 m and 0.9 m, or 5.2 and 3 ft, respectively, totaling 2.5 m or 8.2 ft) is simple to measure from the displacement of the upper surface of unit 10, but similar stratigraphic correlations could not be made across fault F1. Correlation of unit 8-1A across the whole fault zone, however, gives an apparent net vertical

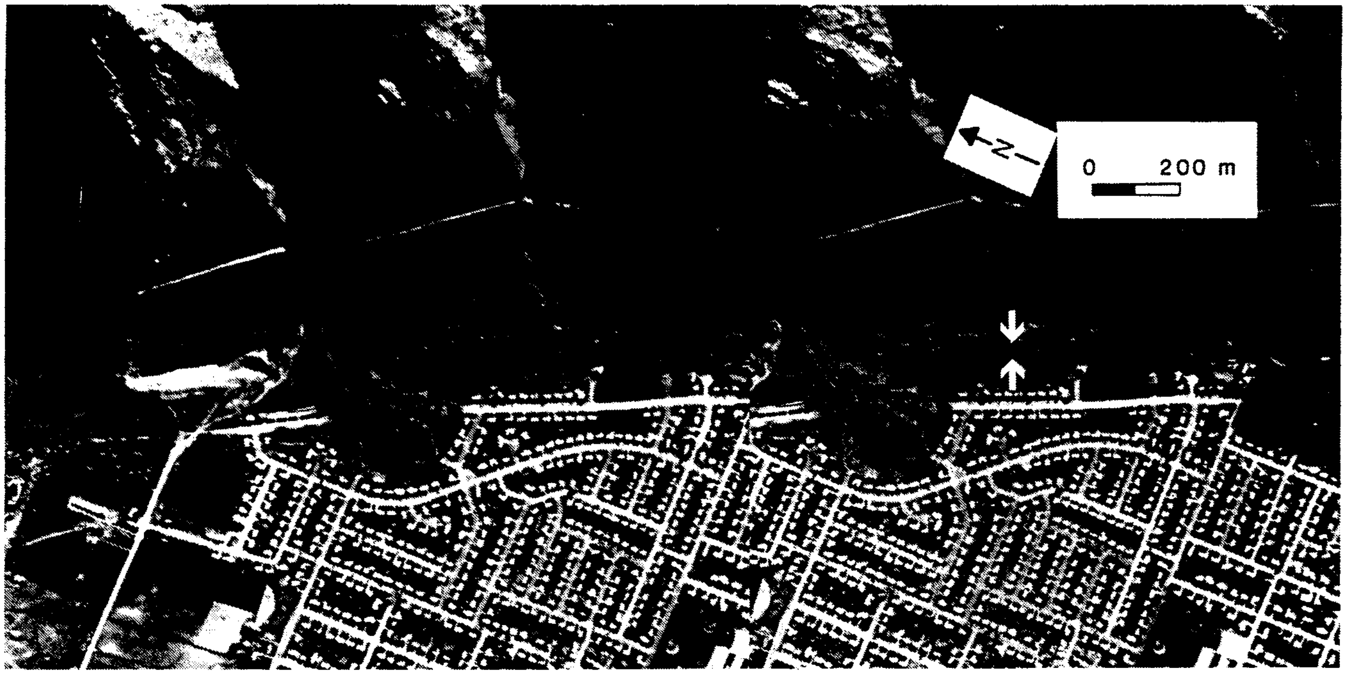


Figure 3. Stereoscopic pair of low-sun-angle aerial photographs of eastern part of Brigham City, Utah; location of the trench site is marked with arrows. Photographs were taken for Utah Geological and Mineral Survey in 1969 or 1970 and are identified as roll 5-8, frame nos. 125 (left photo) and 126 (right photo). Compare with figure 2.

displacement of about 3.5 m (11.5 ft) on fault F1.

Although no slickensides or other absolute measures of fault displacement direction were found, detailed examination of the geomorphology of the trench site showed no evidence of laterally offset channels or levees, and therefore the faults at the trench site probably underwent mostly dip-slip displacement during the surface-faulting events that created the Bowden Canyon fault scarp.

Most of the faults exposed in the Brigham City trench are marked by shear zones as much as 70 cm (2.3 ft) wide. The faults and shear zones generally dip 65° to 80° to the west, although in places they may dip more than 90° (top of fault F1, location 17, 5.5) or be almost flat (middle of fault F2, location 19, 5.5). The flat portion of fault F2 has been inferred to help explain the excessive thickness of fault-scarp colluvium (units 2 and 4) adjacent to fault F3; it is unlikely that these two colluvial wedges, with a total thickness of more than 2 m (6.6 ft), could have been generated by a fault having a total vertical displacement of only 0.9 m (3 ft).

Several tectonic cracks were exposed in the Brigham City trench. The crack closest to fault F3 (location 21, 5-8) appears to be a compound feature; the texture of the disturbed sediment that fills the two cracks is different, and in two places (locations 21, 5-5.5 and 21, 6.5-7) crosscutting relationships indicate that the western crack disturbs the eastern crack and suggest that the western crack is younger. The timing of movement on these compound cracks is unknown because they only disturb units in the footwall, but the cracks presumably formed during two of the faulting events that formed the Bowden Canyon fault scarp. The large crack in the hanging wall (location 14, 3-4) appears to have formed during the last surface-faulting event recorded in the trench because it disturbs units 3 and 5, which were deposited subsequent to the first two events. The stratabound nature of this feature suggests an alternative origin as a large burrow, but the sediment in the crack is very similar to the surrounding deposits and does not contain a higher concentration of organic-rich sediment as do other filled burrows in the trench.

FAULTING SEQUENCE

Despite the complexities discussed above, relations between scarp-colluvial deposits suggest that evidence for three surface-faulting events was exposed in the Brigham City trench (figure 5). Evidence for the oldest event is problematic because of questions about the origin and age of deposits exposed near the base of the trench. The two younger events are better constrained by several AMRT ^{14}C ages on organic-rich sediment from soils on fault-scarp colluvial wedges. Evidence for each of these surface-faulting events is discussed separately in the following section. The methods used to calibrate and interpret the radiocarbon ages and an explanation of how these ages are used to estimate the timing of individual events are discussed later in the report.

EVENT ONE

Unraveling the history of the first event is especially difficult because of the lack of a well-preserved pre-fault surface in the hanging wall, the unusual geometry of unit 5, and the apparent erosion of part of the adjacent footwall. Evidence suggests that movement during the first surface-faulting event occurred on faults F1 and F2 and was followed by fluvial erosion of the pre-fault surface in the hanging wall and part of the adjacent footwall (figure 5). Fluvial (unit 5-2) and colluvial (unit 5-1) sediments were deposited after erosion had modified the fault scarp created by the first event.

The complex stratigraphic relations exposed near the base of the trench can best be explained by substantial post-event-one erosion of both the hanging and foot walls before deposition of units 5-2 and 5-1. Evidence for erosion of the hanging wall includes the lack of a buried soil on the remnants of the prefault surface, the presence of a fluvial channel cut into this surface, and the presence of a fluvial gravel deposit (unit 5-2) at the base of the channel. Erosion of the footwall is apparent because correlation of the upper surface of unit 10-1 in the footwall and reconstruction of the pre-fault surface across the whole fault zone show that about 3.5 m (11.5 ft) of stratigraphic section is missing above unit 9-2A between faults F1 and F2 (location 18, 5), and about 5.5 m (18 ft) of section is missing above unit 9-2 between faults F2 and F3 (location 19, 5). This sediment was eroded by a stream from Bowden Canyon that probably was deflected to flow parallel with the scarp produced by the first event. Unfortunately, the south wall of the trench was not exposed well enough to identify correlative stratigraphic units, and the exact geometry of the channel cut by this stream is unknown. The presence of numerous channels and individual debris-flow units on the Bowden Canyon fan surface, a small post-event-one alluvial fan just north of the trench site (figures 2, 3), and upper Holocene alluvial fan deposits just south of the trench site all suggest that the surface of the Bowden Canyon alluvial fan has been subjected to repeated episodes of alluvial erosion and deposition subsequent to event one.

The timing of the post-first-event erosion episode is undated; however, stream diversion should have been much more likely shortly following the first event because backtilting of the downthrown fan surface would have facilitated channel diversion away from the normal topographic slope of the fan surface. Prograding scarp colluvium would have "regraded" any backtilting of the Bowden Canyon fan surface in a few hundred years or less; thus, stream diversion probably occurred shortly after the first surface-faulting event disturbed the trench site.

Unit 5-2 was deposited concurrent with or immediately following the erosion that postdated event one. Unit 5-1 was deposited after erosion and deposition of unit 5-2. The original extent of unit 5-1 prior to the second surface-faulting event is unknown, but this deposit may have extended some distance eastward of the location of fault F1. Because no correlative deposits have been logged eastward of fault F1, these deposits either have been removed by subsequent erosion or have been incorporated into unit 9-2A. The latter is probably the case because preservation of the soil on unit 9-2A suggests very little subsequent erosion of this surface and because unit 9-2A is much thicker than correlative unit 5-1A. The AMRT ^{14}C ages on soil-organic material from units 5-1A (4340 ± 100 yr B.P.) and 9-2A (4330 ± 70 yr B.P.) support the correlation of the soils on units 5-1 and 9-2 across fault F1.

Several methods can be used to estimate the amount of displacement that occurred during event one. The thickness of fault-scarp colluvial wedges is commonly thought to be one-half to one times the amount of displacement that occurs during a surface-faulting event (Swan and others, 1980; Schwartz and others, 1983). If this relationship holds true in the Brigham City trench, then based on the thickness of scarp colluvial unit 5-1 (0.75 m or 2.5 ft), the amount of vertical displacement on fault F1 from the first event is 0.75 to 1.5 m (2.5 - 5 ft). Displacement on fault F2 cannot be estimated using this technique because no colluvial wedge from movement on this fault strand was recognized in the trench; however, the severe modification of the fault zone by erosion after the first event probably invalidates the use of wedge thickness for calculation of fault displacement during event one. Indeed, given uniform displacements, the first-event colluvial wedge should be thicker than subsequent wedges because the composite fault scarp becomes progressively higher and steeper with each subsequent faulting event (Schwartz and others, 1983, figure 2). As evident in the trench log, unit 5-1 is thinner and has the least wedgelike geometry of all the colluvial wedges in the trench; this deposit probably does not fit the standard models of colluvial-wedge formation.

Another method of estimating first-event displacement is based on the change in surface offset of the Bowden Canyon fault scarp, 50 m (164 ft) north of the trench site. Here a small alluvial fan has been deposited over the fault scarp; the surface offset measured from a topographic profile across the scarp on the younger fan is only 4 m (13 ft), or 1.5 m (5 ft) less than the scarp at the trench site (figures 2, 3, 4). This relationship suggests that the small fan buried the fault scarp that formed during the first event, and thus the difference in surface offset between the two sites of 1.5 m (5 ft) may be equivalent to the total vertical displacement of the first event. The younger fan apparently did not extend far enough south to affect the larger scarp at the trench site because no correlative deposits were exposed in trench BC-1. A separate trench was excavated across the smaller scarp on the younger fan during operations at the Bowden Canyon trench site, but because an active spring was breached, the excavation had to be backfilled before the trench exposure could be logged.

A third method of estimating first-event displacement is to subtract displacement values on the better constrained second and third events from the estimates of the total vertical displacement across faults F1 and F2. As previously discussed, surface offset of the Bowden Canyon fault scarp and correlation of unit 8-1A across the whole fault zone suggest that net vertical displacement across fault F1 is about 3.5 m (11.5 ft). Correlation of soils on unit 5-1A and 9-2A across fault F1 allows measurement of about 1.5 m (5 ft) of post-first-event vertical displacement; thus, displacement during the first surface-faulting event should be about 3.5 m minus 1.5 m, or 2.0 m (11.5 ft less 5 ft or 6.6 ft). Estimates of displacement on fault F2 are even less precise, but the differential erosion of 3.5 to 5.5 m (11.5 - 18.0 ft) of sediment above unit 9-2 between faults F1 and F3 suggests some movement on fault F2 during the first event. The apparent erosion of a soil correlative to unit 9-2A on the remnant of unit 9-2 between faults F2 and F3 (location 19, 5) suggests perhaps 0.5 m (1.6 ft) of displacement on fault F2 during the first event. Thus my best estimates for displacement during the first faulting event are about 2.0 m (6.6 ft) on fault F1 and 0.5 m on fault F2, for a total vertical displacement of about 2.5 m (8.2 ft).

There are several potential problems associated with the interpretation discussed above: (1) texture of sediment and the geometry of unit 5-1 suggest that this deposit may not be a colluvial wedge, (2) unit 9-2 between faults F1 and F2 may be scarp colluvium or graben fill, and (3) unit 5-1 may be distal colluvium correlative with unit 4. These alternative interpretations, however, are difficult to reconcile with the AMRT ^{14}C ages on units 5-2A and 9-2A. Unit 5-1 does not exhibit the classic wedge shape of most fault-scarp colluvial wedges, but gravel clasts in the deposit are imbricated near the fault zone and the deposit is less consolidated than the debris-flow deposits (units 6 and 7) it overlies.

The sediment in unit 9-2 between faults F1 and F2 could be interpreted as scarp colluvium, but this deposit is clearly more like the adjacent silty facies of debris flows and is better consolidated than the overlying colluvial-wedge deposits (units 2 and 4). The pebble imbrication in unit 9-2 is restricted to a narrow (30 cm or 12 in) zone adjacent to fault F2 and may be associated with shearing along this fault strand. The lack of well-rounded pebble gravels in unit 9-2 between faults F1 and F2 also suggests that this deposit is not fault-scarp colluvium. If unit 9-2 was a colluvial wedge, then distinctive well-rounded fluvial gravels from unit 10 should have been exposed in a free face that would have contributed sediment to a colluvial wedge in this position. Finally, if unit 9-2 was a colluvial wedge, then the total thickness of this deposit (2.5 m or 8.2 ft) and

Figure 4. Bowden Canyon fault scarp prior to excavation, view looking southeast; fault scarp is about 8 m (26 ft) high. Location of the Brigham City trench is marked with arrows.

colluvial units 2 and 4 (2.0 m or 6.6 ft) would be almost twice the well-constrained amount of displacement (about 2.5 m or 8.2 ft) across faults F2 and F3 derived from correlation of the surface of unit 10 across these fault strands.

Although a scenario that correlates units 4 and 5-1 across fault F1 is geometrically reasonable, at least one of the AMRT ^{14}C ages from units 5-1A and 9-2A probably would have to be contaminated in order to accommodate this correlation. Contamination is unlikely, however, because no evidence of burrowing or other bioturbation was seen in these deposits.

My best estimate of relations near the base of the trench suggests that the first event formed scarps on faults F1 and F2. Scarp formation was followed soon after by erosion of much of the pre-fault surface and deposition of units 5-2 and 5-1. A soil later formed on the surface of unit 5-1 in the hanging wall and 9-2 in the footwall. The event totaled about 2.5 m (8.2 ft) of net vertical displacement.

EVENT TWO

Soil and slope processes continued to modify the Bowden Canyon fault scarp until the second surface-faulting event disturbed the trench site. This event occurred on all three strands of the fault zone and was followed by deposition of colluvial unit 3 adjacent to fault F1 and unit 4 adjacent to faults F2 and F3 (figure 5). Total thickness of units 3 and 4 (1.3 m and 1.2 m, or 4.3 ft and 3.9 ft, respectively) is about 2.5 m (8.2 ft) and, based on wedge thickness, total vertical displacement during this event was 2.5 to 5.0 m (8.2 - 16.4 ft). The amount of vertical displacement on fault F1 is probably about equal to the thickness of unit 3 because preservation of the pre-second-event soil on unit 9-2A suggests little subsequent erosion of the second-event fault scarp. If the estimates of displacement during event one are reasonable, then net vertical displacement on faults F2 and F3 from the second and third events totaled about 2.0 m (6.6 ft). The thickness of the colluvial wedges formed after the second and third events (1.2 m and 0.8 m, or 3.9 ft and 2.6 ft, for units 4 and 2, respectively) also totals 2.0 m (6.6 ft); thus, displacement on these faults may be about equal to the thicknesses of the colluvial wedges generated by these events. Therefore, my best estimate of net vertical displacement during the second event is about 2.5 m (8.2 ft) across the fault zone, with about 1.3 m (4.3 ft) on fault F1 and 1.2 m (3.9 ft) on faults F2 and F3.

A potential problem with the interpretation discussed above may be expressed in the complex stratigraphy of unit 4. Unit 4-3 is proximal-debris colluvium characterized by loosely packed cobbles and sparse matrix deposited near the base of the fault zone. Unit 4-2 is slope-wash colluvium characterized by better sorting and downslope pebble imbrication. The eastern part of unit 4-2 (location 20, 6.5) contains some discontinuous pockets of organic-rich A-horizon sediment that suggest a soil may have been present on the surface of unit 4-2 prior to deposition of unit 4-1. The stratigraphy in this part of the trench is complicated, however, by the presence of large boulders and very steep slopes. Other interpretations are that the soil-organic material in unit 4-2 is part of now unrecognizable blocks of A-horizon sediment that spalled from the free face of the scarp or that the soil on unit 4-1A and the soil-organic material in unit 4-2 are part of the same soil. In the western part of unit 4 (location 18, 5.5), matrix and clast composition and texture are indistinguishable, suggesting that unit 4 formed as the result of a single faulting event. Unfortunately, there was insufficient organic-rich sediment in units 4-1A or 4-2 for radiocarbon analysis.

EVENT THREE

The third and youngest surface-faulting event recorded in the Brigham City trench probably was accompanied by movement on faults F1 and F3, but only a single colluvial wedge (unit 2) is preserved from this event (figure 5). Some movement on fault F1 must have occurred because correlative units 3 and 4 are in fault contact with fault F1 and appear to be slightly offset. Movement on fault F3 is apparent because unit 4 is also in fault contact with fault F3. Unit 2 lies unfaulted against the free face of fault F3 and

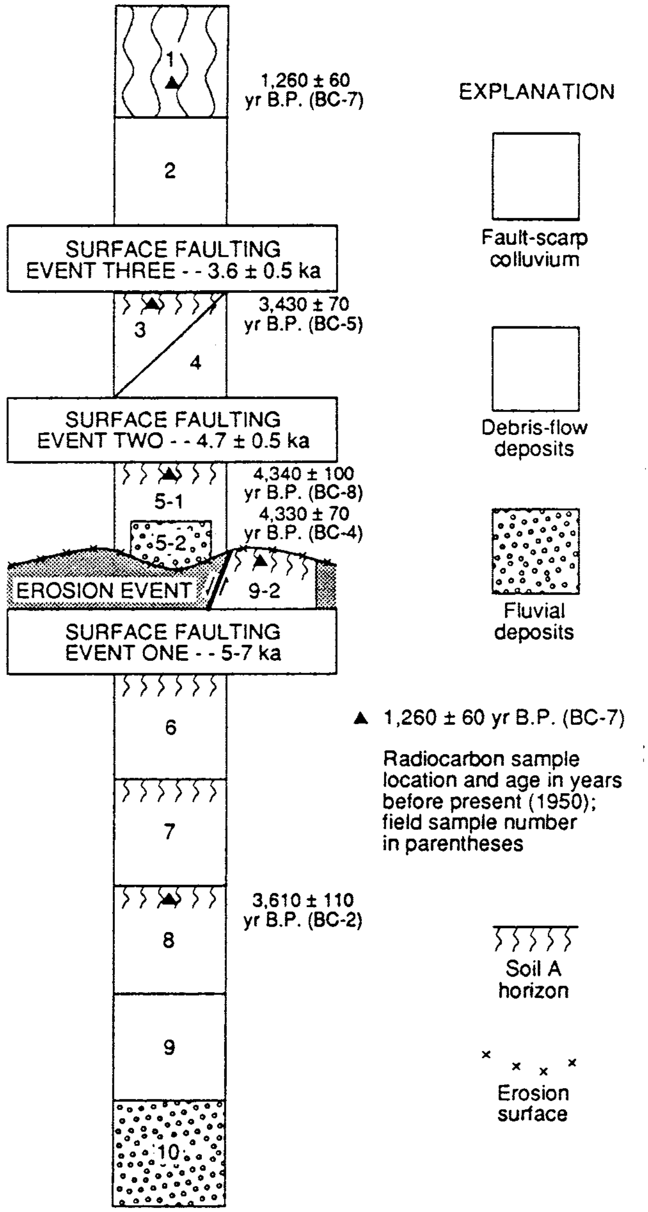


Figure 5. *Schematic diagram showing relationship between surface-faulting events, erosion, and stratigraphic units exposed in the Brigham City trench. Radiocarbon ages are apparent mean-residence-time (AMRT) ages on concentrated organic material from A horizons of soils. Ages of surface-faulting events are estimates derived from stratigraphic relations and AMRT ages calibrated to the calendric time scale (see discussion in text). Note that sample BC-2 probably has been contaminated with younger carbon.*

represents colluvial-wedge deposition from the third event. This is the only unfaulted colluvial wedge and free face exposed in the Brigham City trench. Unit 4 appears to lie unfaulted over fault F2 but, as previously discussed, total offset on fault F3 (0.9 m or 3.0 ft) appears to be insufficient to generate two colluvial wedges (units 2 and 4) more than 2 m (6.6 ft) thick. This apparent discrepancy may be explained by the transfer of some displacement from fault F2 to fault F3, either on a now-obscured flat fault (shown queried on the log at location 19, 5.5) connecting faults F2 and F3, or on an undetected shear zone in unit 9-2 between faults F2 and F3.

The thickness of unit 2 (about 0.8 m or 2.6 ft) suggests vertical displacement during event three of 0.8 to 1.6 m (2.6 - 5.2 ft). If displacement on faults F2 and F3 during the first and second events was about 1.7 m (5.6 ft), however, then the total displacement on these faults (about 2.5 m or 8.2 ft) only allows about 0.8 m (2.6 ft) of vertical displacement during the third event.

As mentioned above, some displacement occurred on fault F1 during the third event, despite the lack of a preserved free face on this fault strand. The lack of a preserved free face can be explained by erosion of the free face on fault F1 and probably some of the upper surface of units 3 and 4 after the third event. This erosion may explain the lack of a soil on the surface of units 3 and 4 directly adjacent to fault F1. Correlation of soils 5-1A and 9-2A yields a total of about 1.5 m (5 ft) of vertical displacement across fault F1 for the second and third events, so if displacement during the second event was about 1.3 m (4.3 ft), then movement on fault F1 during the third event was only about 0.2 m (0.7 ft). Reconstruction of soils 3-A and 4-1A across fault F1 also suggests a maximum of a few tens of centimeters of net vertical displacement during the third event. Therefore, my best estimate of net vertical displacement during event three is about 1.0 m (3.3 ft) across the fault zone, about 0.8 m (2.6 ft) on fault F3, and about 0.2 m (0.7 ft) on fault F1.

RADIOCARBON AGE CALIBRATION AND TIMING OF EVENTS

AMRT AGES

The radiocarbon ages obtained in this study are conventional gas-proportional ^{14}C determinations on organic-rich sediment from the A horizons of modern and buried soils. These age determinations are termed "apparent mean-residence-time" or AMRT ages (Matthews, 1980) because the organic matter in soil A horizons is a mixture of materials having a variety of ages. The organic matter in soils is usually in the form of humus (humic substances) and less-resistant components such as proteins and carbohydrates. The complex origin of this organic matter makes interpretation of AMRT ages and estimation of associated errors much more difficult than interpretations of radiocarbon age determinations on more conventional materials such as charcoal or wood. Despite these problems, an attempt was made to calibrate the AMRT ages obtained in this study to the calendric time scale. The techniques and some of the problems associated with calibrating and interpreting AMRT ages are briefly discussed below.

RADIOCARBON AGE CALIBRATION

The relationship between the radiocarbon and calendric time scales has been shown to be nonlinear because of variable rates of ^{14}C production in the atmosphere (Stuiver and Quay, 1979). Studies of tree rings in Europe and North America show that Holocene radiocarbon ages may be several hundred years too old or too young; these dendrochronologic studies have been used to construct high-precision radiocarbon calibration curves that allow calibration of radiocarbon ages younger than about 9 ka (Stuiver and Kra, 1986). The calibration procedure recently has been simplified through the use of computer software that performs all the necessary calculations (Stuiver and Reimer, 1986).

Several steps are required in the calibration procedure: (1) a laboratory error multiplier must be selected, (2) the applicable calibration data set must be selected, and (3) the age span of the carbon in the sample must be estimated. Error multipliers were not available for the radiocarbon laboratories that analyzed the samples in this study, so a multiplier of 2 was used (Stuiver and Pearson, 1986), thereby doubling the laboratory-supplied one-sigma error limits. The large age-span estimates for AMRT samples (table 1) suggest that the bidecadal data set (Stuiver and Reimer, 1986) is the appropriate one for the samples in this study. The age span of carbon in a soil sample is dependent on many factors such as topographic position, type of biologic activity on and in the soil, sedimentation rate, and climate. The carbon age-span estimates used in this study are based on these factors, as well as on comparisons with other studies of radiocarbon ages of soils (Matthews, 1980; Brown, 1986; Machette and others, 1987, in press). The calibrated radiocarbon ages determined in this study are listed in table 1; in discussion, these age determinations are termed "calibrated AMRT ages" to clearly differentiate them from the original AMRT ^{14}C age determinations.

Calibrated AMRT ages also must be adjusted before they can be used, along with other evidence, to estimate the timing of surface-faulting events because the organic matter in a soil sample already has an AMRT age at the time of burial. The AMRT adjustments listed in table 1 are estimates of the AMRT ages of the sampled soils at the time they were buried; these values must be subtracted from the calibrated AMRT ages in order to estimate elapsed times since soil burial. Data from several trenches on other parts of the Wasatch fault zone (Machette and others, 1987, in press) suggest that AMRT-age adjustments of 100 to 300 years are reasonable values for modern and buried soils exposed in trenches along the Wasatch Front. These values were obtained from AMRT ages on modern soils, as well as from AMRT and conventional charcoal ^{14}C and thermoluminescence (TL) age determinations on buried soils (Forman and others, 1989).

The single AMRT age on the modern soil from the Brigham City trench (1260 ± 60 yr B.P.) is substantially older than the AMRT adjustment values discussed above. At least two explanations for this discrepancy are possible. The first is that this sample was contaminated with older, reworked A horizon sediment, presumably from an exposure of soils 3-A (AMRT age of 3430 ± 70 yr B.P.) and 4-1A in the free face of the fault scarp formed during the third event. An additional source of older carbon is the influx of sediment from older deposits by slope-wash processes active on the steep (24° at scarp midpoint) Bowden Canyon fault scarp. A second and perhaps more likely explanation is related to the amount of time unit 1-2A has been accumulating. This unit is thicker, siltier, and more organic rich than many of the modern soils used for calculating AMRT adjustments elsewhere along the Wasatch fault zone. These differences in soil development are probably related to the fact that this soil has been accumulating at least three times longer (more than 3000 years versus less than 1000 years) than modern soils at other Wasatch trench sites (Machette and others, 1987, in press).

The soil on unit 1-2A is substantially thicker and better developed than the soils on units 3-A and 5-1A; these differences are probably related to the longer amount of time unit 1-2A has been accumulating. Downslope movement of older sediment by slope wash should have increased as the Bowden Canyon fault scarp increased in size and steepness. In addition, sample BC-7 in unit 1-2A is lower in the soil profile than samples from units 3A and 5-1A, so an older age should be expected. These differences in soil-accumulation time, slope steepness, and sampling location suggest that the single AMRT age of 1260 ± 60 yr B.P. from unit 1-2A is a poor analog for adjustments to AMRT ages from units 3-A, 5-1A, and 9-2A. I have chosen to use much lower AMRT adjustment values (table 1) because these values are better sup-

Table 1.
Radiocarbon ages for samples from trench BC-1, Brigham City, Utah

All samples are the fine (< 125 μ) organic fraction of A-horizon sediment from buried or modern soils, concentrated by sedimentation methods (Kihl, 1975) by Rolf Kihl at INSTAAR, University of Colorado. The two radiocarbon laboratories used in this study (PITT—University of Pittsburg Applied Research Center Radiocarbon Laboratory; USGS—U.S. Geological Survey, Menlo Park Radiocarbon Laboratory) were asked to centrifuge these samples during HCL and NaOH treatments in order to recover as much of the finest organic fraction as possible before analysis. Abbreviations in headbar: AMRT, apparent mean-residence-time; ^{14}C, radiocarbon; yr B.P., years before present (1950); ka, thousands of years ago; 1 σ, one-sigma error limit. Leaders (—) indicate not applicable.

Field and laboratory sample numbers	Geologic material, trench unit, and sample depth (m)	AMRT ^{14}C age and lab error (yr B.P.)	Carbon[1] age span (yr)	Calibrated[2] AMRT ^{14}C age (range of 1 σ)	AMRT[3] adjustment (yr)	Time of soil[4] burial (ka)	Remarks
BC-2 USGS 2534	A horizon on debris flow; unit 8-1A; 2.1	3610 ± 110	—	—	—	—	Probably contaminated with younger carbon
BC-4 USGS 2536	A horizon on debris flow; unit 9-2A; 2.6	4330 ± 70	200	4910 (4759-5079)	200	4.7 ± 0.5	Maximum limiting age of second faulting event
BC-5 USGS 2535	A horizon on scarp colluvium; unit 3-A; 1.3	3430 ± 70	200	3700 (3529-3889)	100	3.6 ± 0.5	Maximum limiting age of third (most recent) event
BC-7 PITT-0092	Modern A horizon on slope wash; unit 1-2A; 0.35	1260 ± 60	—	—	—	—	May be contaminated with older carbon
BC-8 USGS 2604	A horizon on scarp colluvium; unit 5-1A; 2.6	4340 ± 100	200	4915 (4659-5249)	200	4.7 ± 0.5	Maximum limiting age of second faulting event

[1]Estimate of range of age of carbon (in calendar years) in sample.
[2]Age calibrated from computer program (Stuiver and Reimer, 1986) using a laboratory multiplier of 2 (doubles laboratory-supplied error limits), and the carbon age span to calculate a moving average. One-sigma error limits are shown as a range of values.
[3]Estimate of AMRT soil age (in calendar years) at time of burial.
[4]Calibrated AMRT age minus AMRT adjustment, rounded to nearest 100 years; error limits discussed in text.

ported elsewhere along the Wasatch Front with multiple TL and radiocarbon age determinations on soils that have accumulated over time periods similar to those of the buried soils in the Brigham City trench.

The final adjusted age values listed in table 1 are termed the "times of soil burial" and probably closely approximate the ages of the two most recent surface-faulting events on the Bowden Canyon fault scarp. The large error limits that bracket these times are my best estimates of the uncertainties associated with the numerous assumptions and adjustments made during calibration and interpretation of the AMRT ages. The errors associated with AMRT adjustments and calibration to the calendric time scale are each at least ± 200 years; if the analytical errors from the radiocarbon laboratories (about ± 100 years) are included, ± 500 years is a reasonable estimation of the error limits defining the times of soil burial. The location of the true age of the faulting event within the time intervals defined by the error limits is unknown but, because of the problems with AMRT adjustments and the anomalously old age of unit 1-2A discussed above, it is probably more likely that the true ages are older rather than younger than the listed values of the time of soil burial.

TIMING OF SURFACE-FAULTING EVENTS

Event One

With the exception of the problematic age of the soil on unit 8-1A (sample BC-2), the only radiocarbon determinations constraining the age of the first surface-faulting event are minimum-limiting AMRT ^{14}C ages from soil A horizons formed on surfaces that postdate the event. Because the time of burial of the soils on units 5-1A and 9-2A (4.7 ± 0.5 ka; see discussion below) probably closely approximates the age of the second event, the age of the first event must predate this time estimate.

Some information on the maximum limiting age of the first event can be derived from regional analysis of the pre-fault deposits and the hydrograph of Lake Bonneville (Scott and others, 1983; Currey and Oviatt, 1985). Reconstructed lake levels indicate that the Brigham City trench site was exposed by the retreating waters of Lake Bonneville about 12 ka. This abandonment was then followed by deposition of at least 8 m (26 ft) of fluvial and debris-flow sediment (units 6, 7, 8, 9, 10) before the first event disturbed the trench site (figure 5). The presence of buried soils on the surfaces of units 7 and 8 suggests that pre-event-one deposits represent at least several thousand years of fluvial- and debris-flow deposition and alternating periods of soil development. Another clue to the age of the pre-fault deposits may lie in the age of Holocene alluvial fans along the Wasatch Front. Machette and others (1987, in press) have identified a middle Holocene (4 - 7 ka) fan-building period, during which much of the sediment in Holocene alluvial fans along the Wasatch Front was deposited. If this period coincided with deposition of most of the Bowden Canyon alluvial fan, as is apparent from recent geologic mapping (Personius, 1988a, 1990), then the youngest pre-event-one alluvial-fan sediments exposed in the trench may have been deposited less than about 7 ka. Therefore, the evidence discussed above suggests that the first event probably occurred 5 to 7 ka.

Event Two

The timing of the second surface-faulting event is constrained by AMRT ^{14}C analyses on organic-rich sediment from buried soils that pre- and postdate the event (figure 5, table 1). The concordance of AMRT ages from the upper parts of units 5-1A and 9-2A (4340 ± 100 yr B.P. and 4330 ± 70 yr B.P., respectively) suggests that these deposits may have formed a single soil-mantled surface prior to the second surface-faulting event. These AMRT ages yield a maximum limiting age for the second event. An AMRT ^{14}C age on the soil developed on the surface of unit 3-A (3430 ± 70 yr B.P.) yields a minimum limiting age for the second event. The calibrated and adjusted times of burial of these soils yield maximum and minimum limiting calendar ages of 4.7 ± 0.5 and 3.6 ± 0.5 ka, respectively, for event two (table 1). Because both maximum limiting ages were on samples collected within a meter or two of the base of the fault scarps, these sites presumably were buried within a few years to tens of years of the second surface-faulting event. This relationship suggests that event two occurred close to the maximum limiting time of soil burial, 4.7 ± 0.5 ka.

Event Three

The timing of the youngest event recorded in the Brigham City trench is constrained by AMRT ^{14}C analyses on organic-rich sediment from a buried soil at the top of unit 3-A (3430 ± 70 yr B.P.) and from the modern soil near the base of unit 1-2A (1260 ± 60 yr B.P.). These AMRT ages provide maximum and minimum limiting ages, respectively, for the youngest surface-faulting event recorded in the trench (figure 5, table 1).

The calibrated and adjusted time of burial of the soil on unit 3-A yields a maximum limiting calendar age of 3.6 ± 0.5 ka for event three. The location of this sample several meters downslope from the fault zones suggests that tens to perhaps a hundred years elapsed between the third surface-faulting event and burial of unit 3-A. I ignored this additional time, however, because of the high rate of colluvial sedimentation on the increasingly steep Bowden Canyon fault scarp and the large error estimates that bracket the time of soil burial.

The minimum limiting age of event three is constrained by the AMRT ^{14}C age of the modern soil overlying the colluvial wedge (unit 2-1) deposited as a result of surface faulting during this event; however, this age (1260 ± 60 yr B.P.) is substantially older than numerous other AMRT ages on modern soils from other parts of the Wasatch fault zone (see discussion above). Therefore, this AMRT age was not calibrated and adjusted, although it probably is a reasonable minimum age for the third and youngest surface-faulting event on this part of the Brigham City segment. The relations discussed above suggest that event three probably occurred before 1260 yr B.P. and most likely occurred close to the maximum limiting time of soil burial, 3.6 ± 0.5 ka.

SEISMOLOGIC IMPLICATIONS

DISPLACEMENT AND EARTHQUAKE MAGNITUDE

Some attempts were made to determine individual displacements for each surface-faulting event, despite the complex nature of the fault zone exposed in the Brigham City trench. Scarp profiling and stratigraphic correlations across the fault zone result in estimates of 5.5 and 6 m (18 and 20 ft), respectively, of net vertical displacement and evidence for three surface-faulting events. These figures yield an average net vertical displacement of about 2 m (6.6 ft) per event. Analysis of colluvial wedges and correlation of soils in the trench suggest that the first event consisted of about 2.5 m (8.2 ft) of displacement, the second event consisted of about 2.5 m (8.2 ft) of displacement, and the third event consisted of about 1.0 m (3.3 ft) of displacement. Although the significance of the apparent decrease

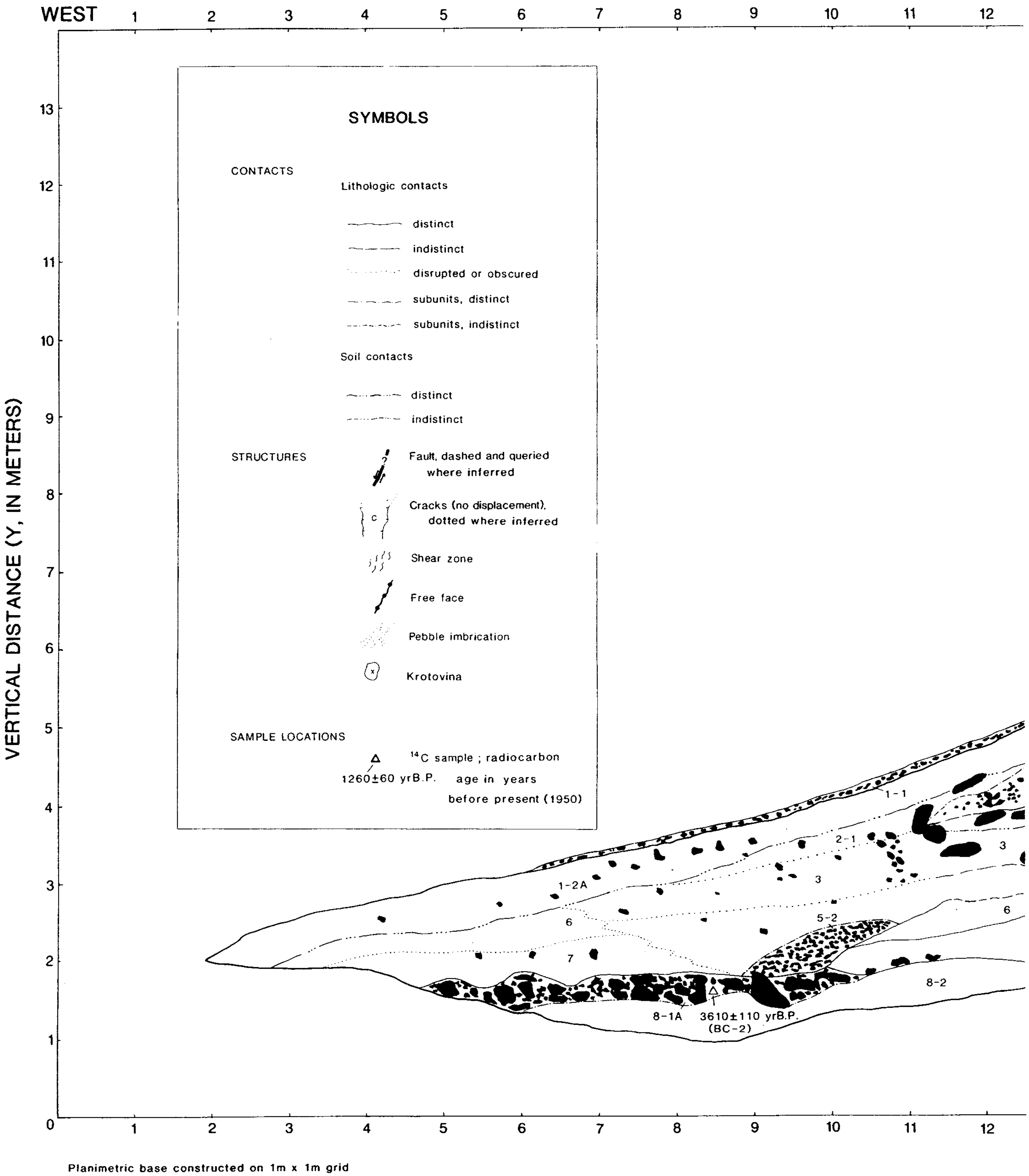
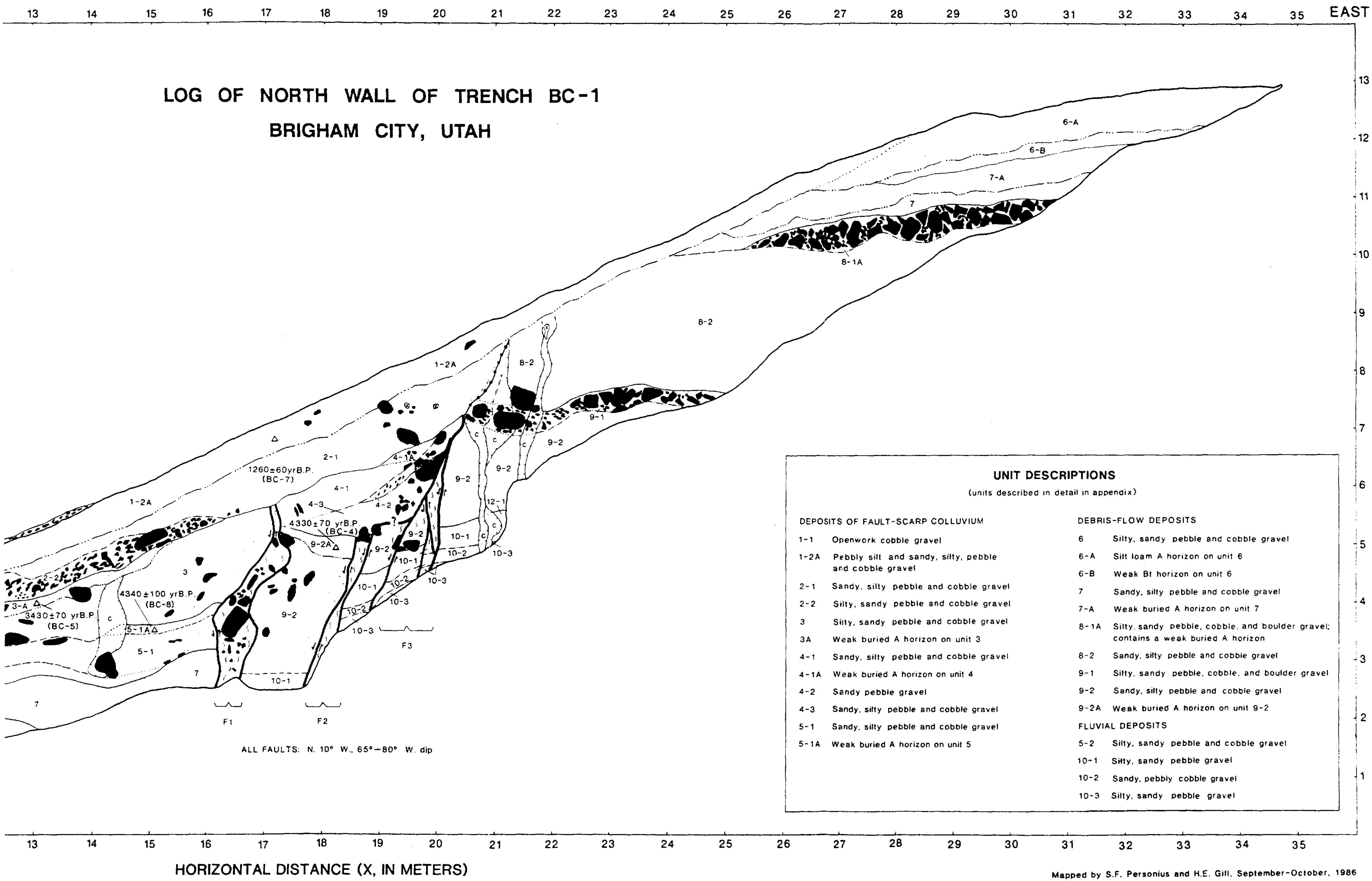


Figure 6. Log of north wall of trench, BC-1, Brigham City, Utah.


LOG OF NORTH WALL OF TRENCH BC-1
BRIGHAM CITY, UTAH
EAST
1260±60yrB.P. (BC-7)
4330±70 yrB.P. (BC-4)
4340±100 yrB.P. (BC-8)
3430±70 yrB.P. (BC-5)
F1
F2
F3
ALL FAULTS: N. 10° W., 65°–80° W. dip
UNIT DESCRIPTIONS
(units described in detail in appendix)
DEPOSITS OF FAULT-SCARP COLLUVIUM
1-1 Openwork cobble gravel
1-2A Pebbly silt and sandy, silty, pebble and cobble gravel
2-1 Sandy, silty pebble and cobble gravel
2-2 Silty, sandy pebble and cobble gravel
3 Silty, sandy pebble and cobble gravel
3A Weak buried A horizon on unit 3
4-1 Sandy, silty pebble and cobble gravel
4-1A Weak buried A horizon on unit 4
4-2 Sandy pebble gravel
4-3 Sandy, silty pebble and cobble gravel
5-1 Sandy, silty pebble and cobble gravel
5-1A Weak buried A horizon on unit 5
DEBRIS-FLOW DEPOSITS
6 Silty, sandy pebble and cobble gravel
6-A Silt loam A horizon on unit 6
6-B Weak Bt horizon on unit 6
7 Sandy, silty pebble and cobble gravel
7-A Weak buried A horizon on unit 7
8-1A Silty, sandy pebble, cobble, and boulder gravel; contains a weak buried A horizon
8-2 Sandy, silty pebble and cobble gravel
9-1 Silty, sandy pebble, cobble, and boulder gravel
9-2 Sandy, silty pebble and cobble gravel
9-2A Weak buried A horizon on unit 9-2
FLUVIAL DEPOSITS
5-2 Silty, sandy pebble and cobble gravel
10-1 Silty, sandy pebble gravel
10-2 Sandy, pebbly cobble gravel
10-3 Silty, sandy pebble gravel
HORIZONTAL DISTANCE (X, IN METERS)
Mapped by S.F. Personius and H.E. Gill, September-October, 1986

in displacement during the third event is unknown, there are several possible explanations. The apparent decrease may be an artifact of the techniques used to estimate surface displacements from trench data, or it may reflect the variability of offset along a surface rupture, or it may in fact reflect a true decrease in fault offset and perhaps a decrease in the magnitude of the causative earthquake. The range of displacements (1.0 - 2.5 m or 3.3 - 8.2 ft) of the three events is similar, however, to many other individual fault displacements measured along other parts of the Wasatch fault zone (Swan and others, 1980; Schwartz and Coppersmith, 1984; Machette and others, 1987, in press). Statistical analysis of historic surface-rupturing earthquakes on normal faults suggests that dip-slip displacements of 1.0 to 2.5 m (3.3-8.2 ft) are associated with earthquakes of magnitude M_S 6.8 to 7.1 (Bonilla and others, 1984).

RECURRENCE

Recurrence-interval information from the Brigham City trench is limited because only the timing of the two youngest surface-faulting events has been constrained by radiocarbon dating. The timing of the second (4.7 ± 0.5 ka) and third (3.6 ± 0.5 ka) events yields a single recurrence interval of 1100 ± 1000 years and an elapsed time since the third (youngest) event of 3600 ± 500 years. Although the associated error limits are large, evidence discussed above suggests that these intervals are geologically reasonable. The timing of the first event is not well constrained, but geologic evidence suggests that it occurred less than 3000 years prior to the second event. If this estimate is correct, then the time elapsed between the youngest event and the present may be longer than the recurrence intervals between the previous two events.

These apparently non-uniform recurrence intervals are common on several of the other active segments of the Wasatch fault zone (Machette and Scott, 1988, figure 6; Machette and others, 1989, figure 3, in press, figure 18) and can be interpreted in several ways. The Brigham City segment may be experiencing a decline in strain accumulation in late Holocene time, or the segment may be accumulating strain at its middle Holocene rate and therefore may be overdue for another surface-faulting event. The segment may also have completed a "cluster" of faulting events in middle Holocene time and is now in a phase of strain accumulation that may last for several millennia. Better data on longer term recurrence is needed to help determine which of these alternatives best explains the pattern of recurrence of Holocene surface-faulting events at the Brigham City trench site.

SLIP RATE

Although estimation of slip rates at the Brigham City trench site is hampered by the lack of age control of the pre-fault surface, a slip rate can be calculated for the period from middle Holocene time to the present. With net vertical displacement estimates from stratigraphic offset and colluvial wedge thicknesses, the second and third events totaled about 3.5 ± 1.0 m (11.5 ± 3.3 ft) of net vertical displacement in the last 4.7 ± 0.5 ka; these values yield a slip rate of about 0.75 ± 0.3 mm/yr (.03 ± .01 in/yr). Because the Brigham City trench is located near the middle of the Brigham City segment, this slip rate may be representative of much of the segment. This conclusion is supported by distribution and size of fault scarps along the length of the segment (Personius, 1988a, 1990).

CONCLUSIONS

The Brigham City trench exposed a record of recurrent Holocene normal faulting on the Brigham City segment of the Wasatch fault zone. Evidence for three surface-faulting earthquakes of probable magnitude M_S 6.8 to 7.1 has been recognized in lower to middle Holocene deposits on the Bowden Canyon alluvial fan just east of Brigham City, Utah. The undated first event consisted of about 2.5 m (8.2 ft) of net vertical displacement and probably occurred 5 to 7 ka; the second event consisted of about 2.5 m (8.2 ft) of net vertical displacement and probably occurred about 4.7 ± 0.5 ka; the youngest event consisted of about 1.0 m (3.3 ft) of net vertical displacement and probably occurred about 3.6 ± 0.5 ka. These relations yield an average displacement of about 2 m (6.6 ft) per event, a middle Holocene slip rate of 0.75 ± 0.3 mm/yr (.03±.01 in/yr), a single recurrence interval of 1100 ± 1000 years between the two youngest events, and an elapsed time since the youngest event of 3600 ± 500 years. This elapsed time is substantially longer than the previous interval (and perhaps the previous two intervals) and suggests that the Brigham City segment has been characterized by non-uniform recurrence of surface-faulting earthquakes in middle and late Holocene time. Several explanations for this pattern are possible. The Brigham City segment may have experienced a decline in strain accumulation in late Holocene time, or the segment may have entered a quiescent phase of strain accumulation between earthquake "clusters." A more ominous scenario is one in which the segment is continuing to accumulate strain at its middle Holocene rate and therefore may be overdue for another surface-faulting earthquake. Additional longer term recurrence data is needed to help determine which of these alternatives best explains the timing of middle and late Holocene surface-faulting earthquakes on the Brigham City segment of the Wasatch fault zone.

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APPENDIX

TRENCH LOG UNIT DESCRIPTIONS

The following unit descriptions are divided into three groups: (1) fluvial deposits, (2) debris-flow deposits, and (3) deposits of fault-scarp colluvium. Within each group, deposits are discussed in order of increasing age; some are described in both hanging wall and footwall sections to aid in correlation. Textures were measured by hand texturing and visual estimates. Sediment colors were very uniform throughout the trench; most dry colors are in a narrow range of grayish brown, from 10YR 7/2 (lightest) to 10YR 4/3 (darkest), with chromas no higher than 4. All gravels consist of clasts of Paleozoic limestone and quartzite. Soil terminology is after Birkeland (1984); facies terminology used to describe fault-scarp colluvial deposits is after Nelson (1987).

FLUVIAL DEPOSITS

5-2 Openwork, clast-supported pebble and cobble gravel, in a discontinuous matrix of silty sand, some of which probably infiltrated from overlying unit 5-1; moderately sorted; clasts about 90% angular to subangular, 10% subround to round; moderately well imbricated. Unit occupies a channel cut in units 6 and 7 and was probably deposited by a stream flowing parallel with the fault scarp after the first faulting event.

Texture	(%)
Silty sand	10
Pebbles	80
Cobbles	10

10-1 Clast-supported pebble gravel, in a matrix of silty sand; moderately well sorted; clasts about 95% round to subround, 5% angular to subangular; well imbricated. Gravels are probably reworked Bonneville lake cycle lacustrine gravels; a discontinuous layer of round to subround cobbles forms a lag gravel on the surface of this deposit.

Texture	(%)
Sand	25
Silt	5
Pebbles	65
Cobbles	5

10-2 Openwork, clast-supported cobble gravel, in a matrix of sand and pebbles; moderately well sorted; clasts about 95% round to subround, 5% angular to subangular; well imbricated.

10-3 Clast-supported pebble gravel, in a matrix of silty sand; moderately well sorted; clasts about 95% round to subround, 5% angular to subangular; well imbricated. Deposit is very similar to unit 10-1; poorly exposed at base of trench.

DEBRIS-FLOW DEPOSITS

6, 6-A, 6-B Clast- and matrix-supported pebble and cobble gravel, in a matrix of silt and sand; poorly sorted; clasts mostly angular to subangular; unstratified. Unit 6-A is the modern soil on unit 6 in the footwall; this soil consists of a thick silt loam A horizon, with moderate, fine to medium, subangular blocky structure. Unit 6-B is a weak Bt horizon formed in the lower part of the unit in the footwall. Unit 6 is poorly preserved in the hanging wall; west of fault F1, much of the deposit has been removed by erosion. Unit 5-2 is deposited in a channel cut into units 6 and 7. At the western end of the trench, unit 6 is obscured by colluviation and soil formation.

Texture	(%)
Sand	20
Silt	40
Clay	10
Pebbles	15
Cobbles	15
Boulders	tr

7-A, 7 (in footwall) Clast- and matrix-supported pebble and minor cobble gravel, in a matrix of sand and silt; poorly sorted; clasts about 70% angular to subangular, 30% subround to round; unstratified except for some very minor imbrication. Unit 7-A is a weak A horizon on surface of deposit that has been infiltrated by clay from unit 6-B.

Texture	(%)
Sand	35
Silt	25
Clay	5
Pebbles	30
Cobbles	5
Boulders	tr

7 (in hanging wall) Clast- and matrix-supported pebble and cobble gravel, in a matrix of sand and silt; poorly sorted; clasts about 60% angular to subangular, 40% subround to round; unstratified except for some very minor imbrication. Deposit is indistinguishable from overlying unit 6 in westernmost part of trench.

Texture	(%)
Sand	35
Silt	20
Clay	5
Pebbles	35
Cobbles	5
Boulders	tr

8-1A Openwork, clast-supported pebble, cobble, and boulder gravel, in a matrix of silty sand; poorly sorted; clasts are a mix of pebbles, cobbles, and boulders to 60 cm (24 in) diameter, about 90% angular to subangular, 10% subround to round; unstratified. Contains remnants of a weak A horizon (sandy loam with weak, fine to medium, subangular blocky structure). Probably is a levee or sieve(?) gravel deposited on the surface of unit 8-2.

Texture	(%)
Silty sand	20
Gravels	80

8-2 Clast- and matrix-supported pebble and cobble gravel, in a matrix of sand and silt; poorly sorted; clasts about 65% angular to subangular, 35% subround; unstratified; well indurated.

Texture	(%)
Sand	30
Silt	30

Clay	5
Pebbles	30
Cobbles	5
Boulders	tr

9-1 Openwork, clast-supported pebble, cobble, and boulder gravel, in a discontinuous matrix of silty sand, some of which probably infiltrated from overlying unit 8-2; poorly sorted; clasts are a mix of pebbles, cobbles, and boulders to 40 cm (16 in) diameter, mostly angular to subangular; unstratified. No evidence of soil development. Thin, discontinuous calcium carbonate rinds are present on bottoms and sides of many cobbles; these are the only calcium carbonate deposits in the trench and are probably relict rinds from fluctuating ground-water levels. Probably is a levee or sieve(?) gravel deposited on the surface of unit 9-2.

Texture	(%)
Silty sand	10
Pebbles	5
Cobbles	80
Boulders	5

9-2 (in footwall) Clast- and matrix-supported pebble gravel, in a matrix of sand and silt; poorly sorted; clasts about 65% angular to subangular, 35% subround to round; unstratified; well indurated.

Texture	(%)
Sand	45
Silt	20
Clay	5
Pebbles	30
Cobbles	tr

9-2A, 9-2 (between faults F1 and F2) Clast- and matrix-supported pebble and cobble gravel, in a matrix of sand and silt; poorly sorted; clasts about 60% angular to subangular, 40% subround to round; unstratified except for some pebble imbrication in a 30-cm-wide (12 in) zone along fault F2. Deposit is less well consolidated and coarser than unit 9-2 in the footwall but better consolidated than overlying colluvial deposits (units 2 and 4). Unit 9-2 may be a colluvial-wedge deposit in this location but more likely is a debris-flow deposit that has been internally disrupted by faulting along faults F1 and F2. Unit 9-2A is a weak, buried A horizon (sandy loam with weak, fine to medium subangular blocky structure) preserved on the eroded surface of unit 9-2; this part of the deposit may consist of sediment that correlates with unit 5-1 in the hanging wall. Radiocarbon analyses indicate that soil-organic material in units 9-2A and 5-1A have the same AMRT age.

Texture	(%)
Sand	35
Silt	20
Clay	5
Pebbles	35
Cobbles	5

DEPOSITS OF FAULT-SCARP COLLUVIUM

1-1 Openwork, clast-supported cobble gravel; moderately well sorted; moderately imbricated. Deposit forms a thin wedge of sorted debris-facies colluvium at the toe of the modern scarp.

1-2A Pebbly silt and clast- and matrix-supported pebble and minor cobble gravel, in a matrix of sandy silt; poorly sorted; weakly imbricated. Modern soil consists of a thick silt loam A horizon (moderate, fine to medium, subangular blocky structure) that infiltrates into underlying unit 2-1 and obscures the contact between these two deposits. Unit postdates the youngest surface-faulting event in the trench.

2-1 Clast-supported pebble and cobble gravel, in a matrix of sand and silt; poorly sorted; clasts about 60% angular to subangular, 40% subround to round; unstratified except for imbricated pebbles along the free face and minor slope-wash imbrication in upper part of the deposit. Deposit fines downslope; most cobbles are in a wedge of coarse debris near the base of the unit adjacent to fault F3. Upper part is infiltrated with silt from overlying soil in unit 1-2A. Contains a few filled rodent burrows. Unit is a colluvial wedge deposited after the third (youngest) surface-faulting event and lies unfaulted against the free face of fault F3.

Texture	(%)
Sand	35
Silt	20
Clay	5
Pebbles	30
Cobbles	10
Boulders	tr

2-2 Openwork, clast-supported pebble and cobble gravel, in a matrix of silty sand, most of which has probably infiltrated from overlying unit 2-1; moderately sorted; clasts are a mix of pebbles, cobbles, and minor boulders, about 60% angular to subangular, 40% subround to round; moderately well imbricated. Unit is a wedge of sorted debris-facies colluvium deposited at the toe of the Bowden Canyon fault scarp after the second faulting event and formation of unit 3-A.

Texture	(%)
Silty sand	10
Gravel	90

3-A, 3 Clast-supported pebble and cobble gravel, in a matrix of silty sand; poorly sorted; clasts about 60% angular to subangular, 40% subround to round; unstratified except for a wedge 40 to 60 cm (16-24 in) wide of imbricated pebbles and minor cobbles adjacent to fault F1; moderately well indurated. Deposit is in fault contact with fault F1 and is disrupted by a large crack or burrow near the middle of the deposit. Unit 3-A is a weak buried A horizon (sandy loam, with weak, fine to medium subangular blocky structure) preserved on the surface of the deposit; this soil has been removed by erosion near fault F1. West of the large crack or burrow, unit 3 is more bouldery, less well indurated, and has more soil-organic material in its matrix. Unit is a colluvial wedge deposited at the base of the fault scarp formed by movement on fault F1 during the second surface-faulting event and probably correlates with unit 4.

Texture	(%)
Sand	35

Silt	15
Clay	5
Pebbles	35
Cobbles	5
Boulders	5

4-1, 4-1A Clast-supported pebble and minor cobble gravel, in a matrix of sand and silt; poorly sorted; clasts about 60% angular to subangular, 40% subround to round; unstratified. Unit 4-1A is a remnant of a weak buried A horizon preserved on unit 4-1 near fault F1 and is probably correlative with unit 3-A. Unit 4-1 is less well consolidated than the debris-flow deposits it was derived from and fines westward. Unit 4 is in fault contact with faults F1 and F3 and probably correlates with unit 3.

Texture	(%)
Sand	35
Silt	20
Clay	5
Pebbles	35
Cobbles	5
Boulders	tr

4-2, 4-3 Clast-supported pebble and minor cobble gravel, in a matrix of sand and silt; poorly sorted; clasts about 60% angular to subangular, 40% subround to round. Unit 4-2 is a wash-facies deposit of imbricated sandy pebble gravel and contains some pockets of organic-rich sediment near fault F3; these organic-rich sediments are either remnants of a buried A horizon, blocks of older A horizon material that fell off the free face of the fault scarp, or are part of a soil that correlates with unit 4-1A. Unit 4-3 is a proximal debris wedge of loose, sandy cobble gravel near fault F3 that fines westward to a sandy, silty pebble gravel near fault F1.

Texture	(%)
Sand	35
Silt	20
Clay	5
Pebbles	30
Cobbles	5
Boulders	5

5-1A, 5-1 Clast-supported pebble and minor cobble gravel, in a matrix of sand and silt; poorly sorted; clasts about 50% angular to subangular, 50% subround to round; very weak pebble imbrication throughout most of the unit east of the large crack or burrow; a wedge of more steeply imbricated gravel is at the base of the deposit adjacent to fault F1. Unit 5-1 is slightly darker than surrounding deposits and is mottled with iron manganese deposits that suggest groundwater staining. Unit is less well indurated than surrounding deposits and is coarser, less imbricated, lighter in color, and less well consolidated west of the crack or burrow. Unit 5-1A is a weakly developed A horizon preserved on unit 5-1 between fault F1 and the crack. Unit 5 was deposited on units 6 and 7, after the first faulting event and fluvial erosion of the pre-fault surface; deposit may in part consist of fluvial gravels associated with this erosion. Deposit may correlate with unit 9-2A. Radiocarbon analyses indicate that the soil-organic material in units 5-1A and 9-2A have the same AMRT age.

Texture	(%)
Sand	35
Silt	20
Clay	10
Pebbles	30
Cobbles	5
Boulders	tr

PALEOSEISMIC ANALYSIS OF THE WASATCH FAULT ZONE AT THE POLE PATCH TRENCH SITE, PLEASANT VIEW, UTAH

by
Stephen F. Personius
U.S. Geological Survey, Denver, Colorado

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PALEOSEISMIC ANALYSIS OF THE WASATCH FAULT ZONE AT THE POLE PATCH TRENCH SITE, PLEASANT VIEW, UTAH

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ABSTRACT

In September, 1985, the Pole Patch trench was excavated across a 1.2-km-long (.7 mi) normal fault on the Pleasant View salient near Pleasant View, Utah, at the boundary between the Brigham City and Weber segments of the Wasatch fault zone. The trench exposed a fault zone that offset deposits of the Bonneville lake cycle with a net throw of about 5.0 m (16.4 ft) (4.6 m or 15 ft with backtilting removed). A series of fault-scarp colluvial wedges provided evidence for three surface-faulting events. The first (oldest) and second events had about 2.2 to 2.5 m (7.2 - 8.2 ft) and 1.5 to 1.8 m (5-6 ft) of vertical displacement, respectively, and occurred between 15 ka and 4.6 ± 0.5 ka. The third (youngest) event had about 0.7 to 1.3 m (2.3 - 4.3 ft) of vertical displacement and occurred about 4.6 ± 0.5 ka. These data yield an average displacement of 1.5 to 1.7 m (5-5.6 ft) per event, a post-Bonneville (15 ka) slip rate of 0.3 ± 0.05 mm/yr (.01 ± .002 in/yr), an average recurrence interval of 5000 ± 333 yr, and an elapsed time since the youngest event of 4600 ± 500 yr. A conservative interpretation indicates that the age of the youngest event is between 4.1 to 5.1 ka but the actual age is unknown.

The Pole Patch fault has been reactivated during relatively few of the faulting events that have occurred on the adjacent Brigham City and Weber segments of the Wasatch fault zone in the last 15,000 years. Correlation of individual events from the Brigham City and Weber segments to the Pole Patch fault is tenuous, but the youngest Pole Patch event might best correlate with the penultimate event recorded at the Brigham City trench site. The ages of the first two events in the Pole Patch trench are poorly constrained, but all three events may have occurred in a relatively short period in early and middle Holocene time, which indicates possible temporal clustering of these events. The amount of displacement from each event appears to have decreased with each subsequent event. Despite the evidence of surface faulting, the short length and unusual structural setting of the Pole Patch fault indicate that this fault is probably incapable of generating major earthquakes, but instead moves in response to surface-faulting events on adjacent segments of the Wasatch fault zone.

INTRODUCTION

The Pole Patch trench (trench PP-1) was excavated in September, 1985 across a 1.2-km-long (.7 mi), northeast-trending fault scarp located about 2 km (1.2 mi) northeast of Pleasant View, Utah (figures 1, 2), during field investigations and mapping of the

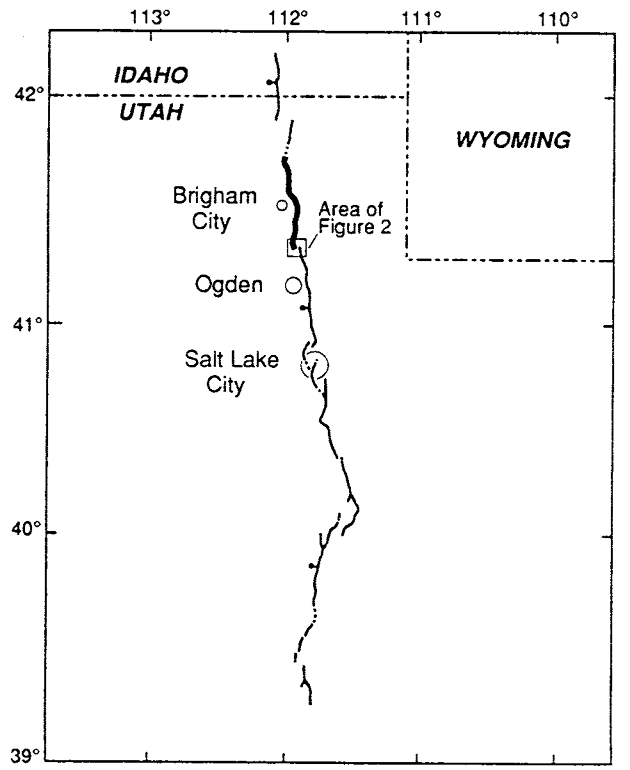


Figure 1. *Index map showing trace of the Wasatch fault zone in southern Idaho and north-central Utah; heavier line marks the Brigham City segment. The location of figure 2 and the area of the Pole Patch trench site is outlined with a box. Fault trace is from Machette and others (1987, in press).*

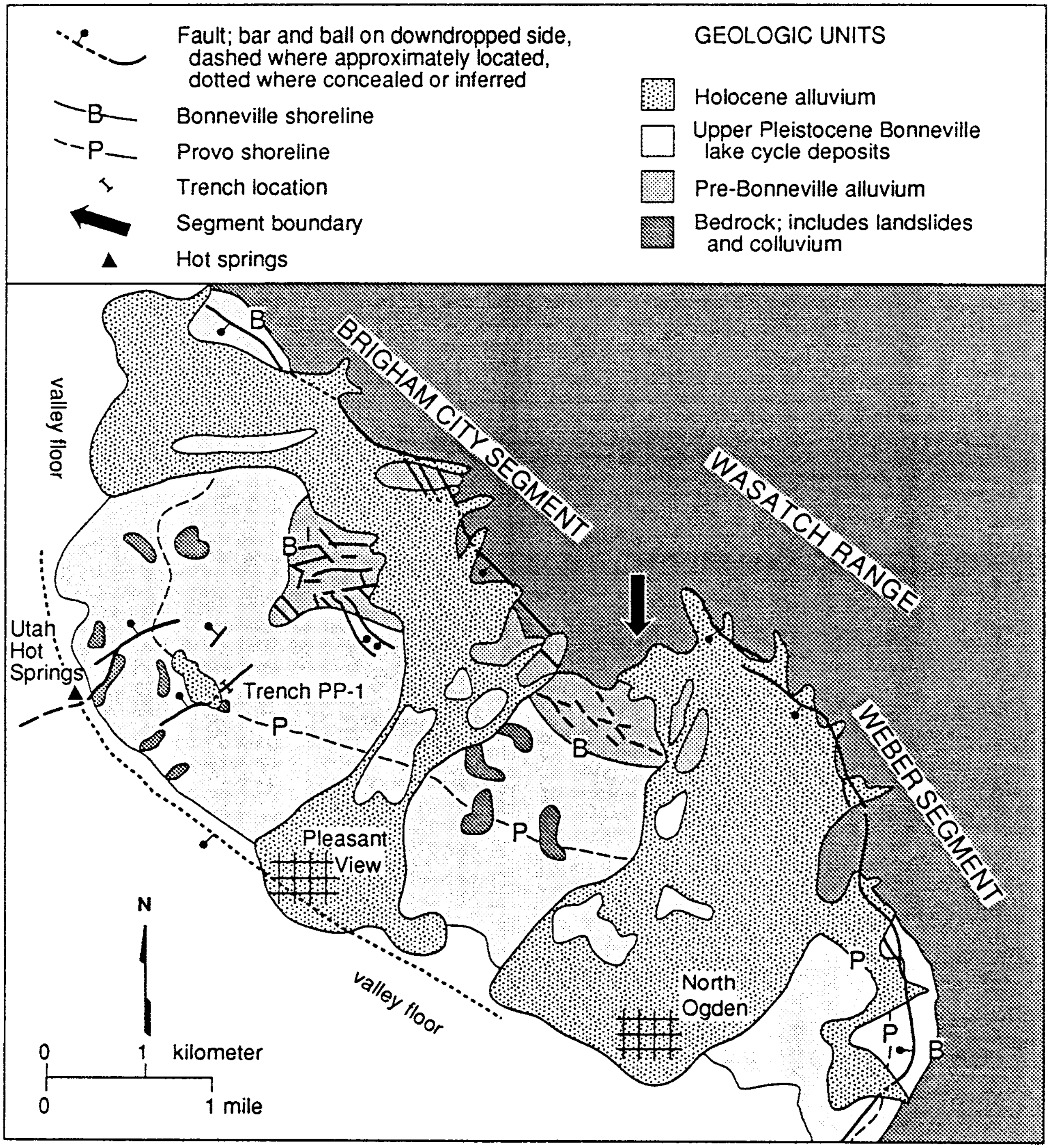


Figure 2. Generalized surficial geologic map of the Pleasant View salient and the Pole Patch trench site; simplified from Personius (1988a, 1990). Location of map area shown in figure 1.

Brigham City segment of the Wasatch fault zone (Personius, 1988a, 1990). Studies of the Brigham City segment were part of a larger effort to better define the timing of individual surface-faulting events along the heavily populated parts of the Wasatch fault zone (Machette and others, 1987, in press; Machette and Scott, 1988; Personius, 1988b, this volume).

This report begins with a description of the Quaternary geologic setting of the region and some of the stratigraphic and structural relations exposed in the Pole Patch trench. The report continues with a description of the most likely sequence of faulting events and the dating and timing of these events, and it concludes with a discussion of some seismologic implications of the Pole Patch trench data. Throughout the report, the term "surface-faulting event" refers to an episode of surface faulting that presumably accompanied a large-magnitude earthquake on the Wasatch fault zone. The term "net vertical displacement" is equivalent to fault throw and refers to the vertical separation of a formerly contiguous stratigraphic horizon or geomorphic surface across a fault zone. Specific features in the following discussion are located by a coordinate pair (x,y) from the corresponding axes on the trench log (page 33); most locations in the text refer to the north wall of the trench, except where the south wall is specified. Detailed descriptions of the deposits in the trench are in the appendix.

GEOLOGIC SETTING

Trench PP-1 is on a topographic and structural salient locally known as the "Pole Patch" after a now-abandoned settlement of the same name. The area is also known as the Pleasant View spur or salient (figure 2), first named by G.K. Gilbert in his pioneering studies of the Wasatch fault zone (Gilbert, 1928). The salient is a foundered block of Proterozoic and lower Paleozoic bedrock (Crittenden and Sorensen, 1985), stranded at an intermediate structural level between the main trace of the Wasatch fault zone and a less-active normal fault that bounds its southwestern edge (Gilbert, 1928; Davis, 1985; Personius, 1988b). The Pleasant View salient also marks the boundary between the Brigham City and Weber segments of the Wasatch fault zone (Personius, 1986, 1988a,b, 1990; Nelson and Personius, 1987).

Much of the Pleasant View salient is covered by lacustrine deposits from the latest cycle of Pleistocene Lake Bonneville, known as the Bonneville lake cycle (Scott and others, 1983; Curry and Oviatt, 1985). This cycle began about 30 ka, when the lake level was near the altitude of modern Great Salt Lake (1283 m or 4210 ft above sea level). The lake level rose to the altitude of the Bonneville shoreline (1584 m or 5200 ft near the trench site) about 16 ka. About 15 ka, the lake overtopped its threshold near Red Rock Pass in southeastern Idaho and the resulting Bonneville flood catastrophically lowered the level of the lake by 115 m (380 ft) to the altitude of the Provo shoreline (1475 m or 4840 ft near the trench site). The lake level remained at the Provo shoreline for a few thousand years before declining rapidly to the level of modern Great Salt Lake by about 11 ka.

Trench PP-1 was excavated in lacustrine sediment of the transgressive phase of the Bonneville lake cycle (figures 2, 3) at an altitude of about 1495 m (4905 ft). Analysis of reconstructed lake hydrographs (Scott and others, 1983, figure 5; Currey and Oviatt, 1985, figure 2) indicates that the trench site was inundated by the rising waters of Lake Bonneville about 18 ka and remained under water until the area was subaerially exposed by the Bonneville flood about 15 ka. Intermittent streams have partially dissected the area around the trench site since it was exposed (figures 3, 4).

The Pleasant View salient is a structurally complex region of poorly exposed Mesozoic-aged thrust faults (Crittenden and Sorenson, 1985) and numerous short (less than 2 km or 1.2 mi long) Quaternary normal faults that are subsidiary to the main trace of the Wasatch fault zone (figure 2). Most of the subsidiary normal faults are only present in older (middle (?) Pleistocene) alluvial-fan deposits, but the fault trenched in this study (herein referred to as the "Pole Patch fault") is one of five normal faults that offset deposits of the Bonneville lake cycle. The Quaternary faults on the salient generally trend either northwest, parallel to the main trace of the Brigham City segment, or northeast, parallel to the Pole Patch fault scarp.

One objective of the Pole Patch trench study was to determine the relations between surface-faulting events on the subsidiary faults on the Pleasant View salient and surface-faulting events on the adjacent main traces of the Brigham City and Weber segments of the Wasatch fault zone. A comparison of the Pleasant View salient with segment boundaries on other major faults (King and Nabelek, 1985; Wheeler, 1987; Wheeler and Krystinik, 1988, in press) led Nelson and Personius (1987) to conclude that the Pleasant View salient is a "nonconservative barrier" to rupture propagation between the Brigham City and Weber segments. Nonconservative barriers are sections of a fault where the orientation of the slip vector changes between adjacent parts of a fault; such sections commonly mark the location of the initiation and termination of fault ruptures (King and Yielding, 1984, King and Nabelek, 1985; King, 1986). These sections are commonly broken by a network of short subsidiary faults (the "process zone" of King and Nabelek, 1985) that may diffuse the energy of earthquake ruptures as they propagate into the barrier (Bruhn and others, 1987). Very little is known about the behavior of subsidiary faults in these barriers, so the data from the Pole Patch trench provide insight into how these types of faults respond to surface-faulting events on adjacent segments.

ANALYSIS OF TRENCH PP-1

STRATIGRAPHY

The stratigraphically lowest and oldest deposit in the trench (figure 6, unit 10), is a coarse lacustrine gravel consisting of corner-rounded pebbles, cobbles, and boulders in a sand matrix. This deposit is interpreted as a lag gravel derived from alluvium and colluvium that predates the Bonneville lake cycle and stratigraphically represents initial inundation of the trench site by the rising waters of Lake Bonneville. The altitude of the trench site indicates that initial occupation and deposition of unit 10 occurred about 18 ka; lacustrine deposition of units 9 through 6 continued until about

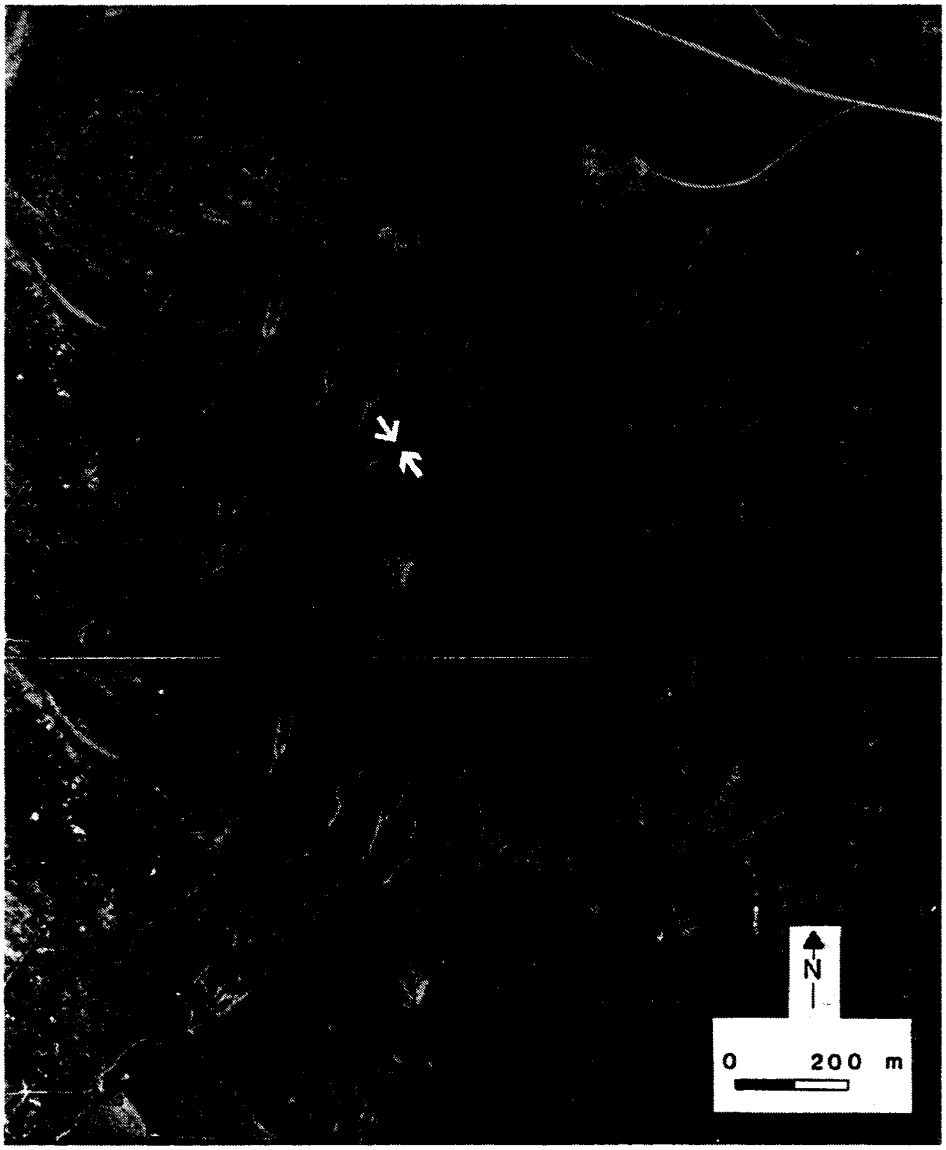


Figure 3. Stereoscopic pair of aerial photographs of western part of the Pleasant View salient; location of the trench site is marked with arrows. Photographs taken 5/23/58 for U.S. Soil Conservation Service and are identified as AAJ-8V-192 (top photo) and AAJ-8V-193 (bottom photo). Note intermittent stream channel that parallels the fault scarp and lack of lateral displacement on offset lacustrine strandlines northeast of the trench site.

Figure 4. Pole Patch trench site, view looking south; scarp is about 5 m (16.4 ft) high. Note intermittent stream channel at base of scarp in foreground. Cut bank at right side of photo is edge of an old gravel pit.

15 ka, when the site was subaerially exposed by catastrophic lowering of the lake by the Bonneville flood. Units 9 through 6 form the bulk of the sediment exposed in the trench and are the source of fault-scarp colluvial deposits exposed in the upper part of the hanging wall adjacent to the fault zone. The ground surface which immediately predated the first surface-faulting event (herein referred to as the "pre-fault surface") is not well preserved in the hanging wall, because this part of the trench apparently was modified by fluvial erosion after the first event.

Three wedges of fault-scarp colluvium (units 3, 4, and 5) overlie the eroded remnants of the original pre-fault surface of unit 6 in the hanging wall. The thickness and texture of these scarp-colluvial deposits are used to determine amounts of displacement and to estimate the timing of individual faulting events in the Pole Patch trench.

Units 1 and 2 are fluvial and colluvial deposits associated with a channel-cutting event that postdates the youngest faulting event recorded in the trench.

STRUCTURES

The Pole Patch trench exposed a relatively simple zone of normal faults, which I have grouped into three fault strands (F1, F2, and F3) for discussion purposes. Stratigraphic correlation of lacustrine units between the hanging wall and footwall is straightforward; projection of the basal contact of unit 7 to the fault zone yields an apparent total net vertical displacement (fault throw) of about 5.0 m (16.4 ft). Apparent throw on individual faults are about 10 cm (4.0 in) of antithetic (down-to-the-southeast) vertical displacement on fault F3, and 50 cm (20 in) and 4.6 m (15 ft) of down-to-the-northwest vertical displacement on faults F2 and F1, respectively. These measurements are apparent values because deposits in the hanging wall have been backtilted into the fault zone. Although a hingline is not clearly expressed in the trench, removal of 3° of backtilt of stratigraphic units in the hanging wall reduces the total net vertical displacement to about 4.6 m (15 ft), with a reasonable error limit of about ± 0.5 m (1.6 ft). Removing this backtilting reduces the true displacement to about 92% of apparent displacement, with most of this correction affecting offset on fault F1. Because the correction for individual events is small, and because the effects of backtilting were difficult to assess during reconstruction of the fault zone, I have ignored backtilting in discussions of the amount of displacement of individual events.

No slickensides or other indicators of absolute slip direction were found in the Pole Patch trench, but the geomorphology of the trench site and field and airphoto examination of strandlines offset by the fault northeast of the trench site (figure 3) showed no evidence of lateral displacement. Therefore the Pole Patch fault appears to have undergone predominantly dip-slip displacement since its formation.

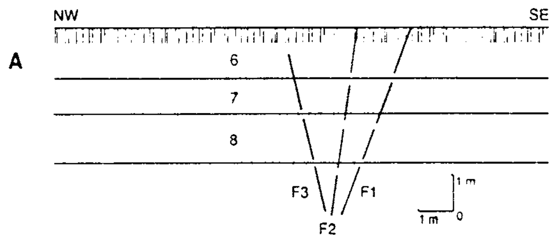
FAULTING SEQUENCE

Relations between scarp-colluvial deposits provide evidence for three surface-faulting events in the Pole Patch trench (figure 5). The first two events are undated, but the timing of the youngest event is constrained by two AMRT (apparent mean-residence-time) ^{14}C ages on organic-rich sediment from soil A horizons. The methods used to interpret the radiocarbon ages and an explanation of other data used to estimate the timing of individual events are discussed later in the report. Evidence for each surface-faulting event is discussed separately in the following section.

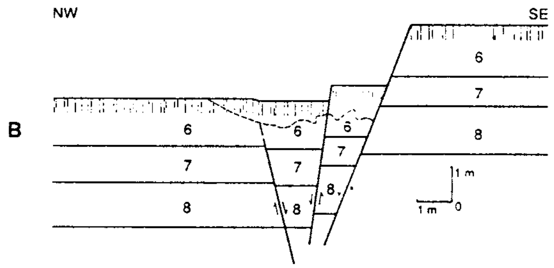
EVENT ONE

The Pole Patch trench site was subaerially exposed by the receding waters of Lake Bonneville about 15 ka as a result of the Bonneville flood. After subaerial exposure, a soil developed on the surface of unit 6. Stratigraphic evidence indicates that faults F1 and F2 ruptured this soil and the surface of unit 6 during the first faulting event, but displacement on fault F3 did not reach the ground surface (figure 5A, 5B). The lack of an A horizon on the present upper surface of unit 6 in the hanging wall can best be explained by a period of erosion that closely followed the first event. Small pods of fluvial sand (unit 5-2) present on the remnants of the pre-fault surface (location 11.5, 4.5) indicate that deposition of fault-scarp colluvium (unit 5-1) occurred concurrent with or closely following the erosion that followed the first surface-faulting event (figure 5C). Evidence for later episodes of fluvial erosion at the trench site include the presence of a buried channel filled with units 1 and 2 and old fluvial scarps (locations 8, 3.5 and 9, 4) in the northwestern part of the trench, and the presence of a modern intermittent stream channel just northwest of the trench site (figures 3, 4).

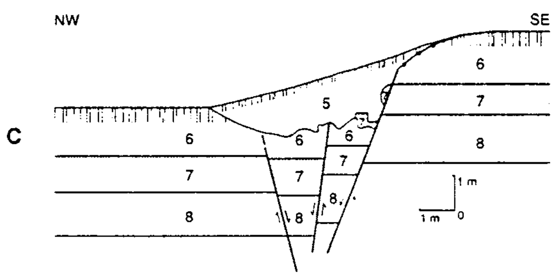
At least two methods can be used to estimate the amount of displacement that occurred during the first event. The thickness of fault-scarp colluvial wedges is commonly thought to be one-half to one times the amount of displacement that occurs during a surface-faulting event (Swan and others, 1980; Schwartz and others, 1983). If this relationship is valid for the Pole Patch trench site, then the thickness of unit 5-1 (about 1.5 m or 5 ft) indicates that the height of the F1 fault scarp (and hence the vertical displacement) was 1.5 to 3.0 m (5-10 ft). Backtilting and erosion prior to deposition of unit 5-1 have increased the thickness of this wedge, so the true



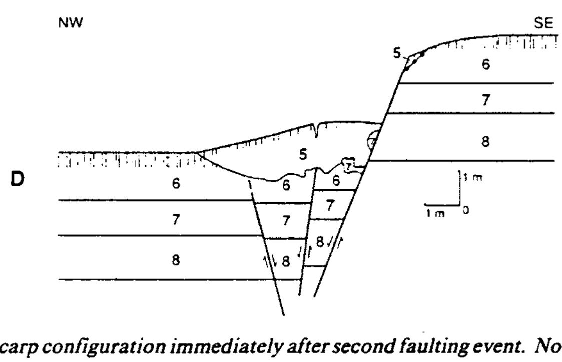
5A. Pre-fault configuration showing restored location of faults F1, F2, and F3, and soil developed on the surface of unit 6; thickness of unit 6 estimated from remnants exposed in the hanging wall of the trench and an exposure in a gravel pit 50 m (164 ft) west of the trench site.



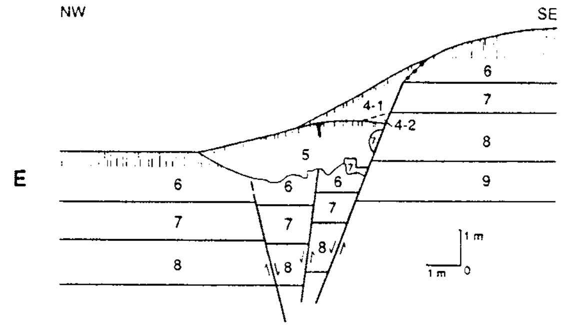
5B. Scarp configuration immediately after first faulting event; note that fault F3 does not break the surface of unit 6. Dashed line represents erosion surface formed after the first event and before deposition of first colluvial wedge (unit 5).



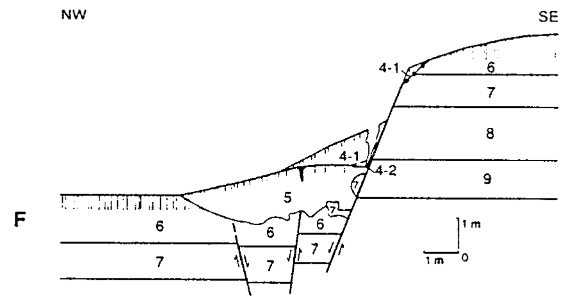
5C. Scarp configuration after erosion event and deposition of first colluvial wedge (unit 5). Location of upper block of unit 7 in unit 5 helps determine minimum offset on fault F1 because block must have spalled from exposure of unit 7 in footwall after first event.



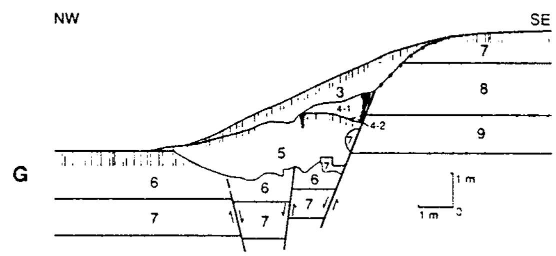
5D. Scarp configuration immediately after second faulting event. Note that surface of unit 5 is faulted about 30 cm (1 ft) below basal contact of unit 7 in footwall. Also note small crack at the hingline in the backtilted surface of unit 5.



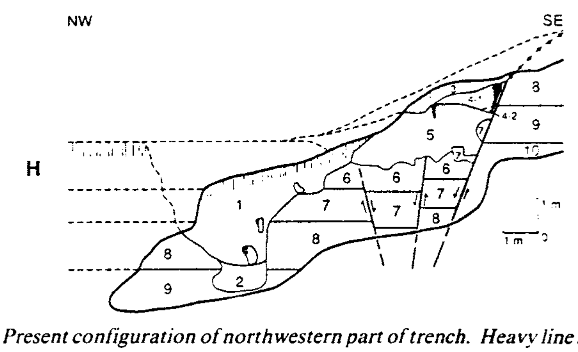
5E. Scarp configuration after deposition of second colluvial wedge (unit 4); location of unit 4-2 is projected from the south wall. Note erosion of thin wedge of unit 5 in footwall.



5F. Scarp configuration immediately after third faulting event; note large crack in unit 4.



5G. Scarp configuration after deposition of third colluvial wedge (unit 3). Note that upper surface of unit 4 in the hanging wall and the thin wedge of unit 4 in the footwall have been truncated by erosion.



5H. Present configuration of northwestern part of trench. Heavy line shows outline of the trench; dashed lines show units removed by erosion. Note post-third-event fluvial channel (geometry of northwestern edge is speculative), and blocks of unit 6 with A horizon attached, in channel-fill deposits (unit 1 and 2); radiocarbon analysis indicates the lowest block of unit 6-A in unit 1 was derived from northwest side of trench (see text). Subsequent fluvial and slope erosion have modified the present surface of the site.

***Figure 5.** Simplified cross sections showing sequential development of the north wall of the Pole Patch trench. Vertical lined pattern represents soil A-horizon development, line and ball symbol represents scarp free face. Numbered units are the same as those on figure 6.*

vertical displacement on fault F1 during the first event is probably less than 3 m (10 ft).

Another method of estimating first-event displacement is based on the textural relations between fault-scarp colluvium and deposits exposed in the footwall from which the colluvium was derived. Unit 5-1 is a silty, matrix-supported gravel composed of carbonate-coated lacustrine pebbles. The abundant silt matrix and predominance of carbonate-coated pebbles in unit 5-1 indicates that this deposit primarily was derived from exposure of units 6 and 7 in a scarp free face in the footwall. If a large exposure of unit 8 was present in the free face, then unit 5-1 should contain an abundance of the friable, sandy, non-carbonate-coated pebble gravel that comprises unit 8. (An example of such colluvium is visible in a roadcut exposure of the Pole Patch fault 20 m (66 ft) downslope of the trench site. Here the oldest wedge of scarp colluvium is a silty, clast-supported pebble gravel probably derived from exposure of unit 8 in the scarp free face). Therefore, perhaps at most 30 to 40 cm (12-16 in) of unit 8 was exposed in the free face after the first event (figure 5B, 5C).

The presence of two large blocks of lacustrine silt (unit 7) in unit 5-1 in the north wall provide additional textural evidence that can be used to place a minimum limit on vertical displacement during the first event. The location of the upper block (location 14, 5.5) requires 1.8 to 2.1 m (6-7 ft) of vertical displacement on fault F1 (figure 5C) because this block must have spalled from a footwall exposure of unit 7 in the scarp free face. The location of the lower block of unit 7 (location 13, 4.5) at the base of the colluvial wedge may have blocked the input of much gravel from unit 8 into unit 5-1. Reconstruction of the north wall of the trench (figure 5B, 5C) therefore yields a net vertical displacement of 1.8 to 2.1 m (6-7 ft) on fault F1 during the first event. Displaced lacustrine units in the north wall indicate about 40 cm (16 in) of net vertical displacement across faults F2 and F3 during the first event; these relations yield a total net vertical displacement of 2.2 to 2.5 m (7.2-8.2 ft) across the whole fault zone during the first faulting event. As is apparent in both walls of the trench, faults F2 and F3 do not extend upward into unit 5-1, so these two structures were not reactivated during later events.

EVENT TWO

The colluvial wedge deposited after event one (unit 5-1) is rotated and faulted adjacent to units 9 and 10 in the footwall, which is evidence of a second surface-faulting event. The upper part of unit 5-1 is slightly darker than the lower part of unit 4, but this boundary is not marked by any significant textural changes in the north wall. However, the presence of a small filled crack in the upper surface of unit 5-1 in the north wall (location 12.5, 6), and the presence of a gravelly proximal debris wedge (unit 4-2; location 14, 6) on the upper surface of unit 5-1 in the south wall are evidence that a weak soil probably separates the surface of unit 5-1 from the overlying unit 4 (figure 5C, 5D).

The thickness of the colluvial wedge from the second event (unit 4) is a maximum of 0.8 m (2.6 ft) in the north wall and is about 0.75 m (2.5 ft) in the south wall. These values imply that net vertical displacement from the second event was 0.75 to 1.6 m (2.5 - 5.2 ft). No soil is preserved on the upper part of unit 4-1 in either trench wall, which implies that either little time elapsed between the second and third events or erosion removed some of the upper surface of unit 4-1. Schwartz and others (1983) and Schwartz and Coppersmith (1984) noted that colluvial wedges formed by similar-sized surface-faulting events tend to decrease in thickness for later events. For these reasons, the thickness of unit 4 gives a minimum estimate of the displacement from the second event.

The texture of colluvial-wedge deposits can again be used to place limits on the amount of displacement that occurred on fault F1 during the second event (figure 5D, 5E). Unit 4-1 is a silty, matrix-supported gravel almost identical to underlying unit 5-1. In the south wall, a proximal debris wedge of imbricated, sandy pebble gravel (unit 4-2) is present at the base of unit 4. The imbricated, sandy texture of this colluvium is somewhat unusual, because proximal debris facies are commonly very poorly sorted and stratified. However, if the sediment exposed in the scarp free face has a loose, sandy matrix, then the basal part of the colluvial wedge will likely have a similar texture, because loose, sandy sediment would slump quickly onto the surface of the hanging wall (Nelson, 1987). Thus, unit 4-2 is thought to have been derived from a small exposure of the friable sandy pebble gravel of unit 8 in the footwall. The presence of a sandy proximal wedge at the base of unit 4 in the south wall, but not in the north wall, indicates that the ground surface prior to the second event (top of unit 5-1) was downdropped adjacent to or just below the contact between units 7 and 8 in the footwall during the second faulting event (figure 5D). Reconstruction of the faulting sequence based on this stratigraphic evidence yields 1.5 to 1.8 m (5-6 ft) of vertical displacement on fault F1 during the second event.

EVENT THREE

The colluvial wedge deposited after the second event (unit 4) has been cracked, rotated, and is faulted against units 8 and 9 in the footwall, which is evidence of a third surface-faulting event (figure 5F). The remnants of a third colluvial wedge, unit 3, are preserved at the top of the hanging wall in both walls of the trench. As with several other units in the trench, fluvial and slope erosion has modified this deposit, but enough of unit 3 is preserved in the south wall to indicate a third event. In the south wall, unit 3 consists of a basal wedge of poorly sorted proximal colluvium (unit 3.2), and an overlying deposit of finer grained wash-facies colluvium (unit 3-1A). In the north wall, unit 3 consists of a thin wedge of wash-facies colluvium with a poorly defined lower boundary. In both walls, unit 3 truncates the large crack formed in the underlying colluvial wedge (unit 4) during the third event and is unfaulted against a free face in the footwall (figure 5G).

The amount of vertical displacement during the third event can be estimated by the thickness of unit 3 and by the estimated displacements from the first two events. In the south wall, unit 3 is a maximum of 0.6 m (2 ft) thick, which implies a net vertical displacement of 0.6 to 1.2 m (2-4 ft). As with the second event, post-faulting erosion and the topographic position of the wedge indicates that this thickness probably gives a minimum estimate of surface displacement. If total displacement across the fault zone is about 5 m (16 ft) and displacement during the first and second events was 2.2 to 2.5 m (7.2 - 8.2 ft) and 1.5 to 1.8 m (5 - 6 ft), respectively, then displacement from the third event must have been 0.7 to 1.3 m (2.3 - 4.3 ft), which agrees with the displacement estimate from the thickness of unit 3. Thus, my best estimate is 0.7 to 1.3 m (2.3 - 4.3 ft) of vertical displacement on fault F1 during the third (youngest) event.

RADIOCARBON AGES AND TIMING OF EVENTS

AMRT AGES AND RADIOCARBON CALIBRATION

The two radiocarbon ages obtained in this study (table 1) are conventional gas-proportional ^{14}C determinations on organic-rich sediment from the A horizons of buried soils. These age determinations are termed "apparent mean-residence-time" or AMRT ages (Matthews, 1980) because the organic matter in soil A horizons is a mixture of materials having a variety of ages. The complex origin of this organic matter makes interpretation of AMRT ages and estimation of associated errors much more difficult than interpretations of radiocarbon-age determinations on more conventional materials such as charcoal or wood. Despite these problems, I have attempted to calibrate the AMRT ages obtained in this study to the calendric time scale, to better assess the timing of surface-faulting events in the trench.

The relationship between the radiocarbon and calendric time scales has been shown to be nonlinear because of variable rates of ^{14}C production in the atmosphere (Stuiver and Quay, 1979). Studies of tree rings in Europe and North America show that Holocene radiocarbon ages may be several hundred years too old or too young; these dendrochronologic studies have been used to construct high-precision radiocarbon calibration curves that allow calibration of radiocarbon ages younger than about 9 ka (Stuiver and Kra, 1986). The calibration procedure has been simplified recently through the use of computer software that performs all of the necessary calculations (Stuiver and Reimer, 1986).

Calibrated AMRT ages must be further adjusted before they can be used to estimate the timing of surface-faulting events, because organic matter in modern soils does not have a radiocarbon age of zero years. The AMRT adjustment is an estimate of this age, which must be subtracted from the calibrated AMRT age in order to estimate elapsed time since the soil was buried by fault-scarp colluvium. Data from several trenches along the Wasatch fault zone (Machette and others, in press) indicate that AMRT-age adjustments of 100 to 300 years are reasonable values for modern and buried soils exposed in trenches along the Wasatch Front. These values were obtained from AMRT ages on modern soils, as well as from AMRT and conventional charcoal ^{14}C and thermoluminescence (TL) age determinations on buried soils (Forman and others, 1989). I have chosen to use an average AMRT adjustment of 200 years for the two radiocarbon ages from the Pole Patch trench.

The final adjusted age values listed in table 1 are termed the "times of soil burial." The error limits that bracket these ages are my best estimates of the uncertainties associated with the assumptions and adjustments made during calibration and interpretation of AMRT ages. The errors associated with AMRT adjustments and calibration to the calendric time scale are each at least ± 200 years; if the analytical errors from the radiocarbon laboratories (usually ± 100 years or more) are included, ± 500 years is a reasonable minimum estimate of the error limits defining the times of soil burial.

Table 1.

[All samples are the fine (< 125 µ) organic fraction of A-horizon sediment from buried soils, concentrated by sedimentation methods (Kihl, 1975) by Rolf Kihl at INSTAAR, University of Colorado. The two radiocarbon laboratories used in this study (PITT—University of Pittsburg Applied Research Center Radiocarbon Laboratory; USGS—U.S. Geological Survey, Menlo Park Radiocarbon Laboratory) were asked to centrifuge these samples during HCL and NaOH treatments to recover as much of the finest organic fraction as possible before analysis. Abbreviations used in headbar: AMRT, apparent mean-residence-time; ^{14}C, radiocarbon; yr B.P., years before present (1950); ka, thousands of years ago.

Field and lab sample number	Geologic material, trench unit, and sample depth (m)	AMRT ^{14}C age and lab error (yr B.P.)	Carbon[1] age span (years)	Calibrated[2] AMRT ^{14}C age (range of 1 sigma)	AMRT[3] adjustment (years)	Time of soil[4] burial (ka)	Remarks
SP-85-4-1 PITT-0093	A-horizon sediment in tectonic crack in colluvium; unit 4; 0.6	4190 ± 125	200	4759 (4419-5039)	200	4.6 ± 0.5	Probably near age of third (most recent) event
SP-85-4-2 USGS 2641	A horizon on block of lacustrine gravel in colluvium; unit 1; 2.3	2390 ± 100	200	2412 (2189-2759)	200	2.2 ± 0.5	Minimum-limiting age of third (most recent) event

[1]Estimate of range of age of carbon (in calendar years) in sample, based on comparison with other studies of radiocarbon ages of soils (Machette and others, in press).

[2]Age calibrated from computer program (Stuiver and Reimer, 1986) using a laboratory multiplier of 2 (doubles laboratory-supplied error limits), and the carbon age span to calculate a moving average. One-sigma error limits are shown as a range of values.

[3]Estimate of AMRT soil age (in calendar years) at time of burial.

[4]Calibrated AMRT age minus AMRT adjustment, rounded to nearest 100 years; error limits discussed in text.

TIMING OF SURFACE-FAULTING EVENTS

Event One

I had hoped that radiocarbon dating of the organic sediment from unit 6-A (location 7, 2) would provide a maximum-limiting age of the first faulting event, because I believed this organic-rich sediment was a fragment of A horizon derived from the pre-fault surface of unit 6 near the fault zone. However, an AMRT ^{14}C age of 2390 ± 100 yr B.P. (radiocarbon years before 1950) on this organic-rich sediment is significantly younger than an AMRT age (4190 ± 125 yr B.P., see discussion below) on similar organic sediment found stratigraphically higher in the trench. Several explanations are possible for this inversion of ^{14}C ages. One possibility is that the older radiocarbon age in the trench is incorrect. A second explanation is that the soil organic matter sampled from unit 6-A may have been contaminated with younger organic-rich sediment from an animal burrow. A third and more likely possibility is that unit 6-A is a fragment of a much younger soil, eroded from an exposure of unit 6 northwest of the trench. This third explanation infers continued soil formation on unit 6 northwest of the trench site, and a subsequent channel-cutting event (and deposition of units 1 and 2) that postdates all the faulting events on the Pole Patch fault (figure 5H). One possible problem with the last interpretation is that the contact between units 1 and 5 (location 10, 5) has been disrupted or obscured in the trench, presumably by subsequent soil formation and slope wash. Unfortunately, no other suitable materials for radiocarbon dating of the pre-fault surface were present in the trench.

As described above, radiocarbon analysis failed to help determine the amount of time that elapsed between subaerial exposure of the trench site and the first (oldest) faulting event. However, this elapsed time can be estimated by comparing the degree of soil development on the remnants of the pre-fault surface of unit 6 in the hanging wall with soil development on an undisturbed site nearby. In an exposure 50 m (164 ft) west of the trench, the modern soil developed on an undisturbed lacustrine sequence similar to the sequence in the trench consists of a 30-cm-thick (12 in) A horizon, overlying a 70-cm-thick (28 in) calcium carbonate (K) horizon. The K horizon (soil horizon terminology from Birkeland (1984) and Machette (1985)) consists of a 5- to 10-cm-thick (2 - 4 in) zone of horizontally laminated carbonate overlying lacustrine pebble gravel that is completely cemented with carbonate. This soil began to form no more than 15 ka, but its development is typical of much older soils in the region. The anomalously large volume of carbonate in the soils in the trench area probably is related to high original calcium carbonate content in the lacustrine sediment, redeposition of the carbonate by ground water, and perhaps to locally high rates of carbonate dust influx in latest Pleistocene time because the site is directly downwind from exposed lake flats. The degree of development of the pre-faulting soil on unit 6 in the hanging wall is difficult to assess because the soil has been partially stripped by fluvial erosion; the thickness of the modern A horizon at the undisturbed site indicates that perhaps 30 to 40 cm (12 - 16 in) or more of the pre-fault surface has been removed. The soil remaining on unit 6 in the hanging wall consists of a silty Bk horizon (unit 6-1) with isolated patches of carbonate in underlying gravels (unit 6-2). The amount of carbonate in unit 6 in the hanging wall also implies a significant amount of time for soil formation and carbonate accumulation prior to faulting and erosion, but less time than that indicated by the development of the undisturbed soil in which carbonate has completely engulfed the B horizon. Although this elapsed time cannot be numerically estimated, it is likely that the first event occurred at least several thousand years after the Bonneville flood (15 ka), in very latest Pleistocene or early Holocene time.

A minimum-limiting age on the first event is provided by an AMRT radiocarbon age of 4190 ± 125 yr B.P. on organic sediment in a tectonic crack formed during the third event (see discussion below).

Event Two

The age of the second event is also poorly constrained. As with the first event, no radiocarbon dates are available to limit the maximum age of this event, but soil relations discussed above imply that both the first and second events probably occurred in very latest Pleistocene or early Holocene time. In addition, the very weak soil preserved on the pre-second-event surface of unit 5-1 indicates that the elapsed time between the first and second events may have been relatively short. The AMRT radiocarbon age of 4190 ± 125 yr B.P. on organic sediment in a tectonic crack formed during the third event (discussed below) also gives a minimum-limiting age of the second faulting event.

Event Three

The age of the third event is constrained by an AMRT radiocarbon age of 4190 ± 125 yr B.P. on organic-rich sediment deposited in a tectonic crack (location 14, 6) in unit 4 during or shortly after the third event (figure 5F, 5G). The sediment in the crack is an organic-rich, pebbly silt and contains a small block of unit 4. This sediment was either tectonically emplaced by shearing along the fault zone, as indicated in the south wall, or fell or washed into an open crack, as indicated in the north wall. In either case, the sediment was derived from part of the now-eroded A horizon of a soil formed on unit 4 in the hanging wall and on units 4 and 6 in the footwall (figure 5E, 5F) and was deposited during or immediately after the surface-faulting event. Thus the AMRT radiocarbon age on the crack sediment is a close approximation of the age of the third event in the Pole Patch trench, and serves as a minimum-limiting age of the first and second events.

To better assess the calendar age of the third event, I used the software of Stuiver and Reimer (1986) to determine a dendrochronologically calibrated age of the crack-fill sample of 4759 yr B.P. and one sigma error limits of +280, -340 years (table 1). In addition to this calibration, the AMRT age of the soil at burial also must be estimated before the time of soil burial (and hence the age of the faulting event) can be estimated. Although the original soil from which the crack fill was derived is no longer preserved, I subtracted an average AMRT adjustment of 200 years from the calibrated age to yield a rounded calendar age of about 4.6 ka (table 1). As should be apparent, the numerous assumptions and corrections used to derive this age indicate that error limits of at least ± 500 years are reasonable. Therefore my best estimate is that the crack in unit 4 was formed and filled during or shortly after the third and youngest faulting event, about 4.6 ± 0.5 ka. A more conservative view of this age estimate indicates that the age of the third event is within the time interval defined by the error limits (4.1-5.1 ka), but that the actual age of the event is unknown.

The AMRT radiocarbon age determined on sediment in the channel-fill deposits (units 1 and 2) in the northwestern part of the trench identifies the time of channel cutting and is a minimum-limiting age for the third surface-faulting event. The AMRT radiocarbon age of 2390 ± 100 yr B.P. yields a calibrated calendar age of 2412 yr B.P. and one-sigma error limits of +347, -223 years (table 1). Subtracting an AMRT adjustment of 200 years yields a rounded calendar age of about 2.2 ± 0.5 ka for the channel-cutting event, which postdates all three surface-faulting events in the trench.

SEISMOLOGIC IMPLICATIONS

DISPLACEMENT AND EARTHQUAKE MAGNITUDE

Despite the evidence of intermittent erosion of colluvial and lacustrine units in the trench, I was able to make reasonable estimates of individual displacements for each surface-faulting event recorded in the Pole Patch trench. Stratigraphic correlation of lacustrine deposits yields an apparent total net vertical displacement of about 5.0 m (16.4 ft) (4.6 m or 15 ft with backtilting removed) and the colluvial stratigraphy exposed in the trench shows evidence for three dip-slip surface-faulting events. These values yield an average net vertical displacement of 1.5 to 1.7 m (5 -5.6 ft) per event, but the texture and thickness of the colluvial wedges indicate that the first event had 2.2 to 2.5 m (7.2 - 8.2 ft) of displacement, the second event had 1.5 to 1.8 m (5 - 6 ft) of displacement, and the third event had 0.7 to 1.3 m (2.3 - 4.3 ft) of displacement. The composite range of displacements is similar to displacements measured at the Brigham City trench site (1.0 - 2.5 m, average 2 m or 3.3 - 8.2 ft, average 6.6 ft; Personius, this volume) and is similar to many other individual-displacement measurements along other parts of the Wasatch fault zone (Swan and others, 1980; Schwartz and Coppersmith, 1984; Machette and others, 1987, in press). Statistical analysis of historic surface-rupturing earthquakes on normal faults suggests that displacements of 0.7 to 2.5 m (2.3 - 8.2 ft) are associated with earthquakes of magnitude M_S 6.7 to 7.1 (Bonilla and others, 1984). However, the short length (1.2 km or .7 mi) and location of the Pole Patch fault at a prominent segment boundary are evidence that this fault probably moves in response to surface-faulting earthquakes on the main trace of the Wasatch fault zone, rather than producing its own earthquakes.

Offset data from the Pole Patch trench seem to indicate that the amount of slip has declined with each subsequent faulting event. This apparent decrease in slip per event may be an artifact of the methods used to estimate displacement, but it might also be related to the fault's response to differences in magnitude or distance from the epicenter of the causative earthquakes. The reduced displacement might also indicate that some of the seismic energy from succeeding earthquakes was absorbed by movement on one or more of the other subsidiary Quaternary faults on the Pleasant View salient.

SLIP RATE

Calculation of slip rates at the Pole Patch trench site is hampered by the lack of age control on the pre-fault surface, but a minimum slip rate can be calculated for the period since the site was exposed by the Bonneville flood. A net vertical displacement value of 4.6 ± 0.5 m (15 ± 1.6 ft) and an age of 15 ± 1 ka yields a post-Bonneville-flood slip rate of 0.3 ± 0.05 mm/yr (.01 ± .002 in/yr). This rate is less than one-third the post-Bonneville slip rate on the adjacent Brigham City (1 to 1.3 mm/yr or .4 -.5 in/yr, Personius, 1988a, 1990) and Weber (1.7 to 2 mm/yr or .7 - .8 in/yr, Nelson and Personius, 1990, in press) segments.

RECURRENCE

Data on the recurrence of surface-faulting events on the Pole Patch fault is severely limited because only the age of the youngest event has been constrained by radiocarbon dating. However, average recurrence intervals can be calculated from the limited age data. The average recurrence interval for post-Bonneville time is 5000 ± 333 years, given three events in the last 15,000 ± 1000 years. An average recurrence interval for the time between the poorly constrained first event and the third event (4.6 ± 0.5 ka) cannot be calculated, but if the first event occurred in very latest Pleistocene or early Holocene time, then the three events in the Pole Patch trench may have occurred in as little as 5000 to 7000 years. This amount of time yields an estimated average recurrence interval that is 2 to 3 times higher than that calculated for post-Bonneville time and thus indicates possible temporal clustering of surface-faulting on the Pole Patch fault in early and middle Holocene time.

SEGMENTATION AND CORRELATION OF EVENTS

The lack of age control on the two oldest surface-faulting events in the Pole Patch trench makes it difficult to correlate these two surface-faulting events with events on the Weber or Brigham City segments. Some speculations can be made, however, about possible correlation of the youngest Pole Patch event with events on the adjacent segments. The Weber segment has been very active since the middle Holocene, with three and probably four events in the last 4000 years; the oldest of these events is thought to have occurred about 3.5 to 4.0 ka (Nelson, 1988; Machette and others, in press). On the Brigham City segment, the last two surface-faulting events occurred 3.1 to 4.1 ka and 4.2 to 5.2 ka (Personius, this volume). The youngest Pole Patch event (4.1 to 5.1 ka) might best be correlated with the penultimate event on the Brigham City segment (4.2 to 5.2 ka), although correlation with any of the other middle Holocene events described above cannot be ruled out.

Relations in the trench show that the Pole Patch fault has been activated by relatively few of the surface-faulting events that have occurred on the Brigham City and Weber segments since the Bonneville flood. Personius (1988b) suggested that as many as 6 to 10 events had occurred on the Brigham City segment while Nelson and Personius (1990, in press) suggested that as many as 10 to 15 events had occurred on the Weber segment since abandonment of the Bonneville shoreline. The three events recorded in the Pole Patch trench might represent larger magnitude events, or ruptures

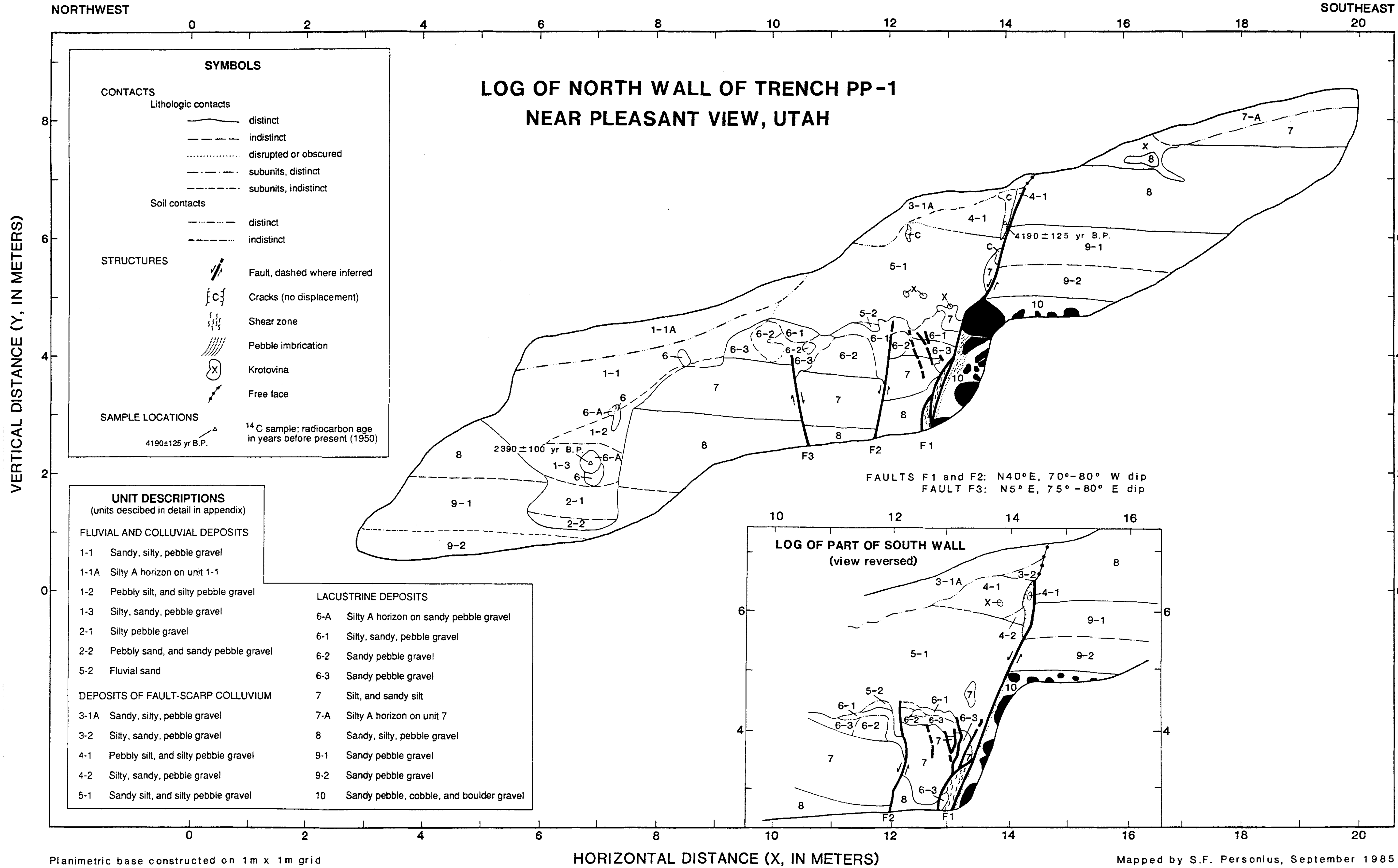


Figure 6. Log of north wall of trench PP-1 near Pleasant View, Utah.

that nucleated or terminated near the Pleasant View salient, or events in which none of the other subsidiary Quaternary faults on the salient were activated.

CONCLUSIONS

The Pole Patch trench exposed a record of three Holocene surface-faulting events on a subsidiary normal fault located on the Pleasant View salient, which marks the boundary between the Brigham City and Weber segments of the Wasatch fault zone. Stratigraphic relations in the trench show that the three events produced about 5.0 m (16.4 ft) (4.6 m or 15 ft with backtilting removed) of vertical displacement in uppermost Pleistocene lacustrine deposits and Holocene colluvium. The undated first (oldest) and second events had 2.2 to 2.5 m (7.2 - 8.2 ft) and 1.5 to 1.8 m (5 -6 ft) of net vertical displacement, respectively, and occurred between about 15 ka and 4.6 ± 0.5 ka. The third and youngest event had 0.7 to 1.3 m (2.3 - 4.3 ft) of net vertical displacement and occurred about 4.6 ± 0.5 ka. These relations yield an average displacement of 1.5 to 1.7 m (5 - 5.6 ft) per event, a post-Bonneville (15 ka) slip rate of 0.3 ± 0.05 mm/yr (.01' ± .002 in/yr), a post-Bonneville average recurrence interval of 5000 ± 333 years, and an elapsed time since the youngest event of 4600 ± 500 years. A more conservative interpretation of the age data indicates that the age of the youngest faulting event is between 4.1 to 5.1 ka, but that the actual age of this event is unknown.

The slip data cited above indicate that movement occurs less frequently on the Pole Patch fault than on the adjacent main traces of the Brigham City and Weber segments. Correlating individual events from the Brigham City and Weber segments to the Pole Patch scarp is tenuous, but the youngest Pole Patch event might best be correlated with the penultimate event at the Brigham City trench site. The absence of evidence of late Holocene faulting in the Pole Patch trench shows that the Pole Patch fault probably did not rupture during either the youngest event on the Brigham City segment or the youngest two or three events on the Weber segment. Because only three post-Bonneville events are recorded in the Pole Patch trench, this fault clearly was not reactivated during many of the faulting events that have occurred on the adjacent segments in the last 15,000 years. However, the three events recorded in the Pole Patch trench may have occurred in a relatively short time span in early and middle Holocene time, which indicates possible temporal clustering of these events. Despite the evidence for multiple surface-faulting events, the short length and unusual structural setting of the Pole Patch fault indicate that this fault is probably not capable of generating major earthquakes, but instead moves in response to surface-faulting events on adjacent segments.

Thus the history of faulting exposed in the Pole Patch trench helps describe the behavior of secondary structures in "process zones" on segment boundaries, but this history shows that a single structure may move in response to relatively few of the surface-faulting events that occur on the adjacent main fault zones. Future studies might determine if the few events recorded in the Pole Patch trench were caused by larger magnitude earthquakes or associated with earthquakes that nucleated or terminated near the Pleasant View salient. Additional paleoseismic studies of other subsidiary faults, as well as the main traces of the Brigham City and Weber segments, are required before a more complete record of the paleoseismic behavior of the Pleasant View salient region can be documented.

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APPENDIX

TRENCH LOG UNIT DESCRIPTIONS

The following unit descriptions are divided into three groups: (1) deposits of alluvium and channel-fill colluvium, (2) deposits of fault-scarp colluvium, and (3) lacustrine deposits of the Bonneville lake cycle. Within each group, deposits are discussed in order of increasing age; some are described in both hanging wall and footwall sections to aid in correlation. Gravel clasts are mostly metasedimentary rock types (quartzites, phyllites, and limestones). The altitude of the trench site (about 1495 m or 4905 ft) indicates that Lake Bonneville first occupied this site about 18 ka (Scott and others, 1983; Currey and Oviatt, 1985). The lake receded below the level of the trench about 15 ka as a consequence of the Bonneville flood, so all lacustrine deposits in the trench were deposited during this 3000-year time period. All listed colors are on dry sediment except where noted. Soil terminology is after Birkeland (1984); facies terminology used to describe fault-scarp colluvial deposits is after Nelson (1987).

DEPOSITS OF ALLUVIUM AND CHANNEL-FILL COLLUVUM

1-1, 1-1A Clast- and matrix-supported pebble gravel, in a matrix of sandy silt; unsorted and unstratified. Unit 1-1A is a dark-brown (10YR 3/3) A horizon with weak, fine to medium platy structure; unit 1-1 is a yellowish-brown (10 YR 5/4) pebble gravel in a calcium carbonate-rich sandy silt matrix. Carbonate is present as coatings on the undersides of pebbles and as horizontal and vertical filaments throughout the unit. As with all other units exposed at the surface of the trench, this unit has been modified by road building, slope wash, and fluvial erosion.

1-2, 1-3 Pebbly silt, and pebble gravel in a silty sand matrix. Unit 1-2 is a pebbly silt and silty pebble gravel; unit 1-3 is a silty, sandy pebble gravel. Both units are colluvium deposited in a stream channel cut in units 6, 7, 8, and 9 in the hanging wall. Blocks of carbonate-cemented pebble gravel (unit 6) are present in both units; radiocarbon analysis of A-horizon sediment (unit 6-A) on the lowest block indicates the block is derived from an exposure of unit 6 northwest of the trench (see text). A fragment of a distinctive iron- and manganese-cemented pebble gravel, derived from an exposure of unit 8 northwest of the stream channel, is present near the base of unit 1-3; this fragment also indicates colluvial transport from exposed lacustrine units northwest of the stream channel (figure 5H).

2-1, 2-2 Sand, and clast-supported pebble gravel in a discontinuous sandy silt matrix. Two distinct subunits are apparent: an upper unit (2-1) of very silty, poorly stratified, weakly carbonate-cemented pebble gravel that contains small scattered lenses of nonstratified, noncalcareous gravels, and a lower unit (2-2) of well-sorted and stratified pebbly sand and sandy pebble gravel. Unit 2 is interpreted as a cut-and-fill sequence of alluvium and colluvium deposited in an intermittent stream channel.

5-2 Sand, medium to coarse, well sorted. Unit is preserved in lenses between base of unit 5-1 and eroded surface of unit 6 and was deposited during fluvial erosion of the hanging wall after the first faulting event.

DEPOSITS OF FAULT-SCARP COLLUVIUM

3-1A Grayish-brown (10YR 5/2) matrix-supported pebble gravel, in a sandy silt matrix; unit is an organic-rich A horizon. Deposit has much less carbonate in matrix and fewer carbonate-coated pebbles than underlying unit 3-2. Some pebbles in upper 25 cm (10 in) of deposit are aligned parallel to slope. Unit is wash-facies colluvium, derived from units 7 and 8 in the footwall, and lies unfaulted against a free face in the footwall; no sheared sediment is apparent along the free face.

3-2 Light-brownish-gray (10YR 6/2) clast-supported pebble gravel, in a silty sand matrix; unsorted and unstratified; less carbonate in matrix, and fewer, thinner patchy carbonate coats on pebbles than underlying unit 4. Unit is a wedge of proximal colluvium derived from units 7 and 8 in the footwall. The unit was deposited on unit 4 and truncates fault F1 and the crack in unit 4. Deposit lies unfaulted against a free face in the footwall; no sheared sediment is apparent along the free face. Unit only exposed in south wall.

4-1 Light-yellowish-brown (10 YR 6/4) sandy, pebbly silt and matrix-supported pebble gravel in a sandy silt matrix; unsorted and unstratified. Pebbles were derived from an exposure of unit 6 in footwall; most are completely covered by calcium-carbonate coats from deposition in unit 6; younger, thicker coats on bottoms of pebbles are from carbonate deposition in unit 4-1. Unit also has both horizontal and vertical stringers and filaments of carbonate throughout the deposit. Unit is nearly identical in texture to unit 5-1, except for a change in color (unit 5-1 is slightly darker) that may indicate a weak buried soil on unit 5-1. A large crack filled with organic-rich A-horizon sediment is present in unit 4 along fault F1 in both walls of the trench; in the south wall, the organic-rich sediment in the crack contains a fragment of unit 4-1. Unit 4-1 was derived from units 6 and 7 in the footwall after the second surface-faulting event and is in fault contact with units 8 and 9 in the footwall.

4-2 Light-yellowish-brown (10YR 6/4) clast-supported pebble gravel, in a matrix of silty sand; poor to moderately sorted, moderately imbricated. Most pebbles have thin, discontinuous carbonate coats. Deposit is a wedge of proximal colluvium, derived from a small exposure of unit 8 in a free face in the footwall after the second surface-faulting event. Unit only exposed in south wall.

5-1 Pale-brown (10YR 6/3) sandy, pebbly silt, and matrix-supported pebble gravel in a matrix of sandy silt; unsorted and unstratified. Unit becomes more silty and less pebbly upward. Pebbles were derived from an exposure of unit 6 in footwall; most are completely covered by calcium-carbonate coats from deposition in unit 6; younger, thicker coats on bottoms of pebbles are from carbonate deposition in unit 5-1. Unit also has both horizontal and vertical stringers and filaments of carbonate throughout the deposit. Unit contains small, poorly consolidated blocks of better sorted, carbonate-cemented pebble gravel (unit 6) and blocks of lacustrine silt (unit 7) along fault F1 near the base. Animal burrows (krotovena) are scattered throughout the deposit. The contact with overlying unit 4-1 is marked by a distinct color change that probably reflects a very weak soil formed on the darker, upper part of unit 5-1; no other textural change was evident at this boundary. In the south wall, this contact is overlain by a small proximal-debris wedge (unit 4-2). A small crack filled with organic-rich sediment is present near the upper surface of unit 5-1 in the north wall, about 2 m (6.6 ft) west of fault F1. Unit 5-1 was derived from exposure of units 6 and 7 in the footwall after the first surface-faulting event and is in fault contact with units 9 and 10 in the footwall.

LACUSTRINE DEPOSITS

6, 6A, 6-1, 6-2, 6-3 Clast-supported pebble gravel, in a carbonate-rich sandy silt to sand matrix; well sorted and stratified to poorly sorted and unstratified. Three subunits are apparent. Unit 6-1 is a light-gray (10YR 7/2), coarse (pebble diameter averages about 1 cm or 0.4 in) pebble gravel, poorly sorted and unstratified; unit is siltier and more friable than lower units. Unit 6-2 is a light-gray (10YR 7/1), fine (pebble diameter averages about 0.5 cm or 0.2 in) pebble gravel, moderately sorted and stratified; unit is less silty and better cemented with carbonate than overlying unit 6-1, and it grades into and interfingers with underlying unit 6-3. Unit 6-3 is a very pale-brown (10YR 7/3), well-sorted, sandy pebble gravel (pebble diameter averages about 0.5 cm or 0.2 in), deposited at moderate to steep (5-15°) original dips; thin carbonate coats are present on bottoms of some pebbles. Unit 6-3 also contains a few thin, discontinuous lenses of silt, and discontinuous pods of sand at base of unit at contact with underlying unit 7. The textural differences between unit 6-1 and underlying units 6-2 and 6-3 are probably related to pre-first-event soil development and post-first-event fluvial erosion. In unit 6, fault F2 is marked by extensive carbonate cementation, probably related to ground water circulating along the fault zone. Some deposits of unit 6 have been dragged down along fault F1 and also fill cracks in the upper surface of unit 7. Several detached blocks of unit 6, some with A-horizon sediment attached (unit 6-A), have spalled into a fluvial channel and are buried in younger colluvium (unit 1) in the northwestern part of the trench. Unit 6 has been completely removed from the footwall by slope wash and fluvial erosion.

7-A, 7 Silt and fine sandy silt, in thin (1-2 mm or 0.04 - 0.08 in) parallel beds, slightly sandy and pebbly at top and base; contains abundant *Amnicola* gastropod shells. Unit 7-A is a dark-brown (10YR 3/3, moist) A horizon with moderate, medium-granular structure; unit 7 is a very pale-brown (10YR 8/4) silt and sandy silt. Carbonate is common in horizontal and vertical stringers and filaments, as rare nodules, and as complete coatings on a few pebbles; less carbonate is present in interior of soil peds in unit 7 in footwall. In hanging wall, the upper 10 to 20 cm (4 - 8 in) of unit is oxidized to a brown color (7.5YR 5/4, moist), probably as a result of circulating ground water; ground-water circulation is also indicated by stringers of carbonate that cut across faults F2 and F3 and cracks in unit 7. Carbonate stringers are more common in hanging wall, probably because of more extensive cracking. Upper surface of unit 7 in hanging wall has 20 to 30 cm (8 - 12 in) deep cracks filled with gravel from overlying unit 6. The northwesternmost exposure of unit 7 in the hanging wall (location 8, 3.5) has a very weathered surface texture and appears to be a formerly exposed fluvial scarp now buried by channel-fill colluvium (unit 1-2).

8 Very pale-brown (10YR 7/4), clast-supported pebble gravel, in a sandy and silty matrix; pebbles have maximum diameters of 5 cm (2 in) and are angular to subrounded with many flat pebbles. Moderately well sorted; deposited in thin to medium (>10 cm or 4 in), parallel beds of pebbles, interbedded with thin (> 5 cm or 2 in), matrix-rich beds and lenses of pebbles. A few thin, sandy pebble beds, as much as 2 m (6.6 ft) in length, have been cemented and stained to a very dark-brown color with iron and manganese oxides. Calcium carbonate commonly cements sand and fine pebbles to undersides of larger pebbles throughout the unit. Bedding is less distinct near fault F1.

9-1, 9-2 Light-yellowish-brown (10YR 6/4), clast-supported pebble gravel, in a sand and minor silt matrix, parallel bedded. Two subunits are apparent. The upper unit (9-1) is similar to overlying unit 8, but with a less silty matrix and better sorting within beds. Thin (< 5 cm or 2 in) openwork pebble gravel beds are common, interbedded with less-well-sorted, thicker (5 - 10 cm or 2 - 4 in), sandier pebble gravel beds. The lower unit (9-2) is similar to unit 9-1 but with sandier matrix; sandy beds in unit 9-2 contain more ground water, and appear as distinctive dark bands in exposure; both units contain discontinuous beds stained and cemented with iron and manganese oxides similar to those in unit 8. The units are similar in both the footwall and the hanging wall, except that the contacts between units 9-1 and 8 and between units 9-1 and 9-2 are less distinct in the hanging wall. Unit shows some drag along fault F1 in footwall.

10 Clast-supported pebble, cobble, and boulder gravel, in a matrix of pebbly sand. Upper 15 cm (6 in) is a very sandy pebble gravel, similar to unit 9, but sandier and less well sorted, with minor, thin (2-3 cm or 0.8 -1.2 in) beds of sand. Upper pebble gravel grades downward to cobble and boulder gravel in a matrix of sandy pebble gravel. Cobbles and boulders (diameters to 0.5 m or 1.6 ft) are generally subrounded to subangular (corner rounded), and most have thin, discontinuous carbonate coats. Some of the cobbles and boulders appear to have been rotated by the faulting, but none were broken; the fault appears to have deviated around the larger clasts. Some cobbles and boulders have oriented pebbles cemented with carbonate to the clast faces adjacent to fault F1. Much of the fabric in the sand and pebble matrix adjacent to fault F1 is oriented and sheared parallel to the fault zone. Unit 10 is interpreted as a reworked lag gravel from the pre-lacustrine alluvial and colluvial deposits present at the land surface prior to the rise of Lake Bonneville.